

Systematic Review

Fruit Waste-Derived Adsorbents for Water Treatment: A Systematic Review on Performance, Mechanistic Insights and Operational Perspectives

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Abstract

Emerging compounds in water, ranging from dyes to pharmaceuticals, negatively impact living organisms and challenge the industries responsible for their release. These pollutants exhibit chemical persistence and resistance to conventional treatment processes. Adsorption is considered an effective and accessible approach, particularly when low-cost and renewable materials are employed. The Problem-Intervention-Comparison-Outcome (PICO) framework and Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines were followed. A structured search of Scopus was conducted to identify English-language original peer-reviewed articles published between 2016 and 2025 addressing the use of fruit waste (FW)-derived adsorbents for water decontamination. After independent screening, 528 studies were included. Risk of bias was assessed qualitatively. Due to substantial heterogeneity in materials, contaminants, and experimental designs, findings were synthesized narratively. FW-derived adsorbents were evaluated in terms of synthesis routes, physicochemical characteristics, adsorption mechanisms, kinetic and equilibrium behavior, process optimization and regeneration performance. Correlations were observed between surface functionalization, material properties and contaminant-specific removal efficiency, while limitations were noted for multi-component systems, regeneration stability, standardization and scale-up. By integrating material design with process-level considerations, this review outlines priorities for advancing FW valorization toward practical and sustainable water treatment applications.

Keywords: fruit waste; water treatment; adsorption kinetics; isotherm modeling; process optimization; adsorbent regeneration



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1. Introduction

Wastewater treatment represents a critical cornerstone for safeguarding water resources and protecting the health of both ecosystems and human populations alike. Although conventional chemical, biological, and physical treatment technologies can remove a broad range of pollutants, their widespread implementation is hindered by elevated costs, significant energy consumption and the generation of undesirable secondary environmental consequences [1–3]. Compounding this issue, the increasing complexity of wastewater matrices, driven by the progressive introduction of emerging contaminants, further challenges the effectiveness of established treatment systems. As a result, heightened focus

is directed toward the development of sustainable and cost-effective solutions [4–9] that reconcile high decontamination efficiency with a reduced environmental impact.

Adsorption constitutes a particularly recurrent and well-documented alternative owing to its operational simplicity, rapid implementation and broad applicability in removing pharmaceuticals, dyes, pesticides, heavy metals, etc. from aqueous matrices. Biomass-derived materials have demonstrated remarkable versatility in this field. Excellent removal efficiencies are reported for pharmaceuticals like sulfamethoxazole, ciprofloxacin, sulfamethoxazole, ketoprofen, carbamazepine, salicylic acid, paracetamol, diclofenac, and iodixanol [10–12]. Similarly, the successful remediation of dye-contaminated aqueous media using composites from nut husk [13], metal–organic frameworks [14], and nano-lignin [15] has yielded performances frequently exceeding 200 mg/g. These materials have also been used for multi-component pesticide removal [16,17] and for the elimination of organic acids [18]. In the same manner, various functionalized agricultural residues have proven effective for the sequestration of heavy metal ions such as Cu^{2+} , Pb^{2+} , Zn^{2+} , Cr^{3+} , Ni^{2+} , and Mn^{2+} [19–22].

Despite these promising results, considerable heterogeneity persists in material preparation methods, characterization protocols, experimental conditions, and performance metrics. Adsorption capacities are frequently reported under highly optimized laboratory conditions that seldom reflect realistic water matrices or operational constraints. Variations in pH, initial contaminant concentration, adsorbent dosage, contact time, and regeneration methodology are often examined independently without adequate reference to process feasibility. An integrated perspective that systematically connects adsorbent design with operational parameters and scalability is therefore necessary to rigorously assess technological viability.

Within this context, fruit waste (FW) has emerged as a particularly attractive precursor for adsorbent synthesis. The fruit-processing industry generates substantial quantities of residues represented by peels, seeds, stalks, and pomace [23], which routinely pose considerable environmental and logistical disposal challenges. The conversion of such fruit-processing residues into functional adsorbents simultaneously reduces the environmental impact of waste disposal and affords low-cost materials well-suited for water decontamination. From a clean technology perspective, this strategy not only supports environmentally sound water treatment but also offers a renewable alternative to fossil-derived activated carbons through efficient biomass valorization. The intrinsic physicochemical composition of fruit residues, typically rich in cellulose, hemicellulose, lignin, and an array of oxygen-containing functional groups, provides opportunities for targeted surface and structural modification. However, the extent to which these compositional features translate into reproducible and scalable adsorption performance remains insufficiently consolidated. Although numerous research has demonstrated the potential of FW-derived materials as effective adsorbents, the available literature remains fragmented. Most investigations emphasize maximum adsorption capacity or removal efficiency, with limited consideration of adsorption kinetics under dynamic conditions, multi-component systems, regeneration stability or integration into existing treatment schemes. Comparative evaluations encompassing synthesis pathways, surface functionalization strategies, adsorption mechanisms and operational robustness across contaminant classes remain scarce, thereby hampering the identification of coherent structure-performance relationships and impeding the formulation of well-grounded research priorities.

To address these gaps, the present review focuses on the examination of advances in FW-derived adsorbents for sustainable water treatment reported over the period 2016–2025. Using adapted Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines and the Problem–Intervention–Comparison–Results (PICO)

framework, this work critically analyzes the literature to (i) summarize synthesis strategies and adsorption performance, (ii) evaluate the influence of operational parameters on process optimization, (iii) elucidate the governing adsorption mechanisms and regeneration efficiency, and (iv) identify key challenges and future research directions. By positioning FW as a renewable and low-cost precursor, this review accentuates its potential as a practical and environmentally responsible alternative to conventional adsorbents. Particular attention is devoted to adsorption kinetics, regeneration potential, operational robustness, and scalability, yielding comparative and process-oriented insights that establish meaningful connections between preparation methods, material characteristics, adsorption behavior, and viable operating conditions.

2. Research Methodology

This review was envisioned to analyze the scientific literature on the use of FW-derived adsorbents for the removal of water contaminants. To ensure the inclusion of high-quality and relevant studies, the research question integrated the PICO framework and PRISMA 2020 guidelines, with adaptations specific to adsorption research [24,25].

Within PICO, the components were defined as: problem (P): water contamination with persistent pollutants; intervention (I): application of the adsorption process for water remediation; comparison (C): comparative analysis of various fruit wastes as precursors for adsorbent synthesis; outcomes (O): feasibility and efficacy of water contaminant removal through retention on low-cost adsorbents.

In accordance with PRISMA 2020, a study protocol was developed a priori and consistently applied throughout the review. It defines the objectives, eligibility criteria, search strategy data extraction, and risk of bias assessment methods. The protocol was not registered in a public database considering that formal registration is not required for environmental systematic reviews. However, it is available in the Supplementary Material S1 along with the PRISMA 2020 checklist (Supplementary Material S2).

The timeframe 2016–2025 was selected to capture recent progress in biomass valorization, adsorbent synthesis techniques and adsorption-based water treatment. Restricting the analysis to this period ensures that the evaluated studies reflect the current state of development in FW-derived adsorbents. A structured search was conducted in Scopus in January 2026. The database was selected due to its comprehensive coverage of environmental engineering and adsorption research. Gray literature and non-indexed sources were not included and are acknowledged as limitations of the review exhaustiveness.

Inclusion criteria enclosed the next items: (I1) keywords were required to appear in the “article title, abstract, keywords” fields of the database; (I2) studies had to address water decontamination (verified through automated screening for “water”, “pollutant”, “contaminant”); (I3) articles had to specifically concern water contaminant removal through adsorption; (I4) research had to utilize FW as precursors for adsorbent synthesis (screened using the term “fruit”); (I5) the publication span was restricted to 2016–2025; (I6) the document type was limited to original “articles”; (I7) only articles in the “final” publication stage were considered; (I8) the source of the paper had to be a peer-reviewed “journal”; (I9) all selected papers had to be written in English.

The following exclusion criteria were applied: (E1) papers unrelated to the topic of FW-derived adsorbents were discarded; (E2) studies published outside the 2016–2025 window were removed; (E3) papers classified as reviews were eliminated to focus on primary data; (E4) content included in books or conference proceedings were excluded to ensure a high standard of peer review; (E5) articles written in languages other than English were omitted; (E6) papers not available in full-text format were excluded from the final analysis.

The search executed in the Scopus database utilized a targeted Boolean formula: (TITLE-ABS-KEY (water) AND TITLE-ABS-KEY (pollutant OR contaminant) AND TITLE-ABS-KEY (adsorption) AND TITLE-ABS-KEY (fruit)) AND PUBYEAR > 2016 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (EXCLUDE (EXACTKEYWORD, "Catalysis") OR EXCLUDE (EXACTKEYWORD, "Catalyst") OR EXCLUDE (EXACTKEYWORD, "Photocatalysis")).

Two reviewers independently screened titles, abstracts and full texts for eligibility. Discrepancies were resolved through discussion and consensus.

Data extracted from the eligible studies included: study details: authors, year of publication; adsorbent details: FW, adsorbent preparation method, characterization techniques; experimental conditions: contaminant type, adsorption parameters; adsorption performance: removal efficiency, adsorption capacity; adsorption modeling: kinetics, isotherms, statistical treatment; regeneration and reuse: performance over multiple cycles.

As no standardized tool exists for the evaluation of risk of bias in environmental adsorption studies, predefined criteria were developed specifically for this review and applied consistently by two reviewers. These criteria were tailored for FW-derived adsorbents focusing on experimental design (synthesis reproducibility, replication, use of controls and clear description of experimental conditions), adsorbent characterization (surface area, porosity and functional groups), adsorption modeling (appropriate isotherm and kinetic modeling, statistical treatment) and regeneration and reuse (assessment of adsorbent performance over multiple cycles). Each study was rated as low, moderate or high risk of bias according to how widely these domains were addressed.

Due to the substantial heterogeneity of materials, contaminants, and experimental conditions, findings were synthesized narratively rather than via meta-analysis.

Reporting bias and certainty of evidence were not formally assessed due to narrative synthesis; this is acknowledged as a limitation.

The PRISMA flow diagram illustrating the selection process is presented in Figure 1. The completed PRISMA 2020 checklist is provided as Supplementary Material S2.

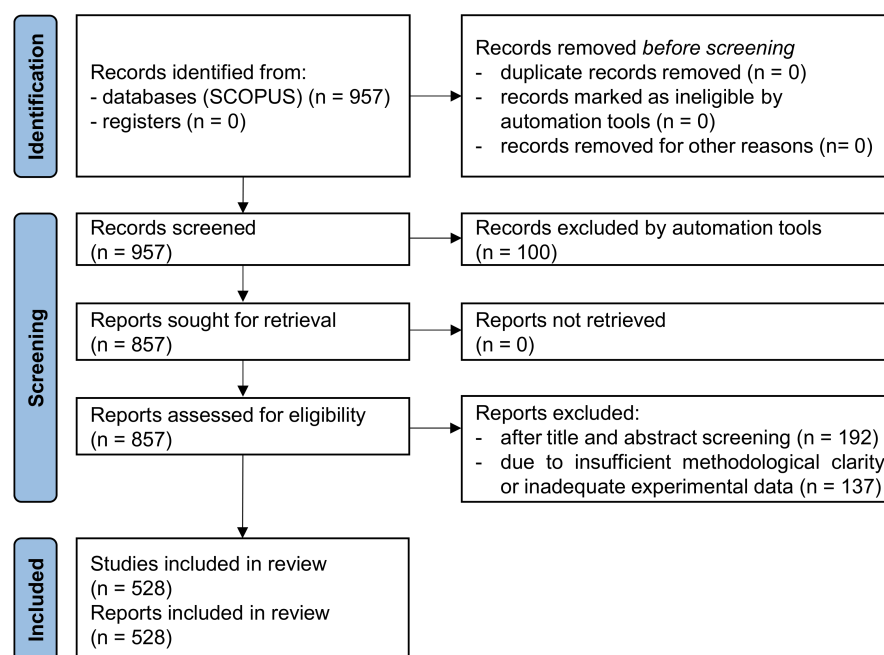


Figure 1. PRISMA 2020 flow diagram illustrating the screening, eligibility assessment and final selection of records included in the review.

After the screening procedure, the selected records were exported in RIS format for bibliometric analysis using VOSviewer software (version 1.6.20). This allowed for the identification of thematic clusters, knowledge gaps and emerging research trends, which are integrated into the discussion to provide a process-oriented overview of FW-derived adsorbents for sustainable water treatment.

3. Results and Discussion

3.1. Overview of the Selected Publications

The application of the PRISMA procedure ensured a thorough evaluation of the current state of knowledge. The search strategy in the Scopus database using a Boolean formula led to 957 records. No records were removed prior to screening, and 100 records were excluded by automation tools, leaving 857 reports sought for retrieval.

According to the bibliometric analysis, 35% (300 papers) of these studies were published in the first half of the decade (2016–2020), with the remaining 557 papers from 2021 to 2025 indicating an escalating interest in FW-derived adsorbents. Geographically, China and India were the dominant contributors, with 259 and 147 records, respectively. Saudi Arabia, Brazil, and Iran each had over 50 publications, while Malaysia, Pakistan, Egypt, South Korea, and Turkey combined had 186 articles. The primary subject areas were “Environmental Science”, “Chemistry”, and “Chemical Engineering”, reflecting the interdisciplinary nature of water decontamination and waste valorization. Notably, over 40% of the papers were published in high-visibility journals with *Chemosphere*, *Environmental Science and Pollution Research*, and *Water Science Technology* as the most frequent venues.

Bibliometric mapping via the VOSviewer software provided deeper insights into collaborative networks and thematic clusters. A co-authorship analysis of 3522 authors identified 86 individuals with at least five publications, forming six distinct collaborative clusters (Figure 2). A keyword co-occurrence analysis (threshold of 5 occurrences) generated six thematic clusters (Figure 3), categorizing the field into specific pollutant targets: heavy metal ions (red), pesticides (green), dyes (blue), pharmaceuticals (olive) and inorganic pollutants (purple). The turquoise cluster focuses on the physico-chemical factors affecting the adsorption, such as pH, temperature, and dosage.

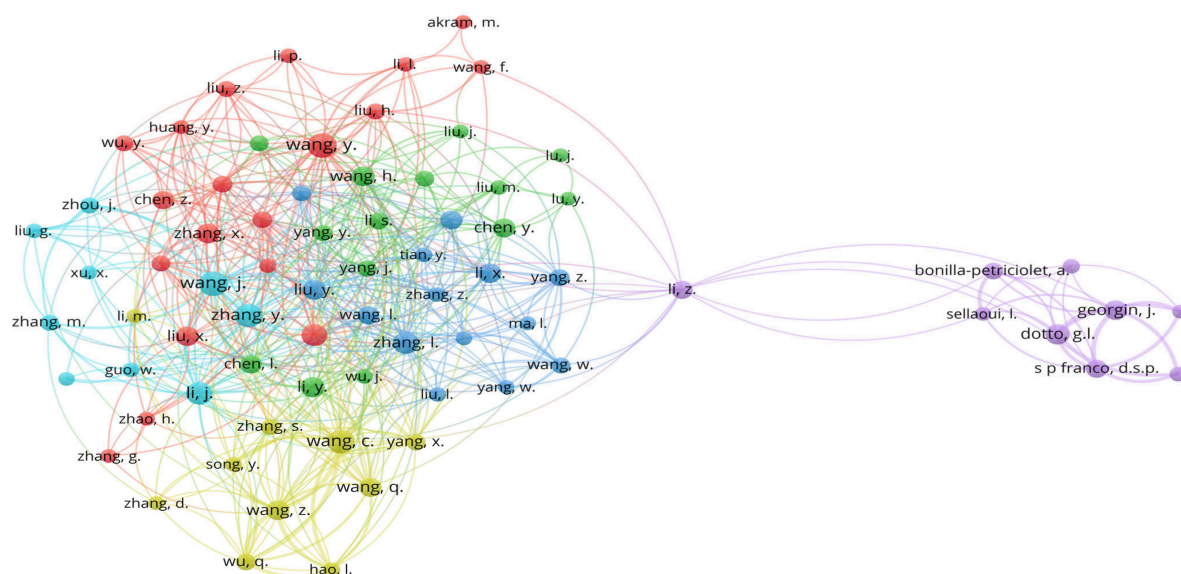


Figure 2. Co-authorship network of the studies retrieved from Scopus, depicting collaborative relationships among authors and the strength of research collaboration within the field.

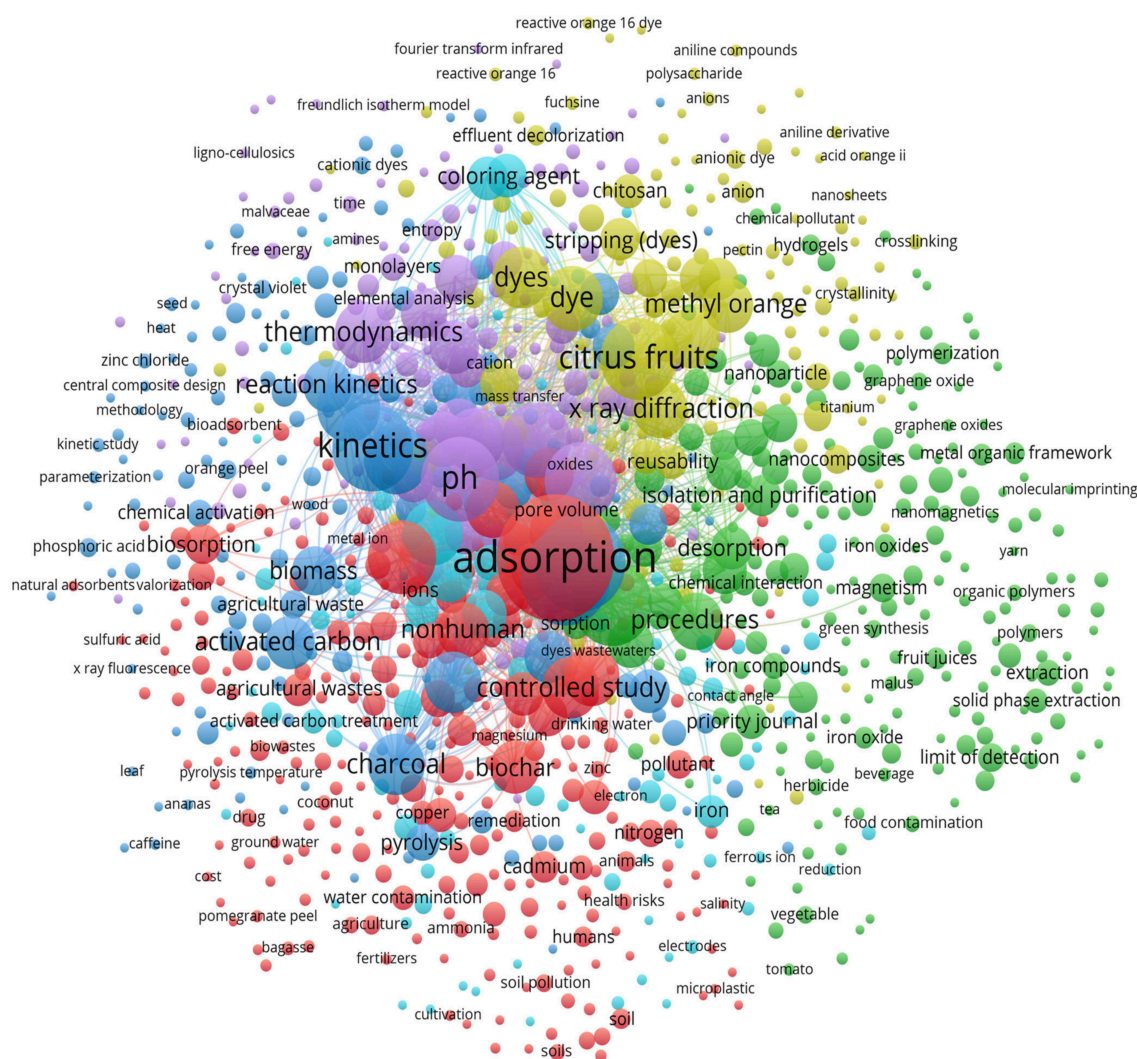


Figure 3. Network of keyword co-occurrence from the Scopus-retrieved records, illustrating the frequency and relationships between key terms to highlight research trends within the field.

After completing the bibliometric analysis, the 857 reports were assessed for eligibility. Following title and abstract screening, 192 records were excluded. The full texts of the remaining items were evaluated and 137 reports with insufficient data or clarity were removed, leaving a total of 528 studies. Of these, 204 were cited. The cited references were selected based on a combination of experimental reliability, methodological soundness, practical relevance and their ability to illustrate key findings and represent major trends. This approach ensured the highlighting of the most informative and impactful studies while keeping the manuscript concise and focused.

Publication tendencies reveal an increasing focus on FW-derived adsorbents in areas such as adsorption mechanisms, kinetic and equilibrium modeling and process optimization. This shift underscores the need for engineering-focused synthesis over isolated performance reporting, motivating the detailed analysis presented in the succeeding sections. This surge also reflects growing regulatory pressure on wastewater discharge, along with the growing integration of circular economy concepts into water treatment research.

3.2. Persistent Water Pollutants

Persistent water pollutants vary in physicochemical properties, chemical complexity, and ionic nature. They pose long-term ecological and health risks and require versatile and efficient remediation strategies, including retention on FW-derived adsorbents. The survey

of records retrieved from the Scopus Database for 2016–2025 identified several classes of water contaminants targeted by these materials. Organic pollutants primarily include dyes, pharmaceuticals, and pesticides, often featuring complex aromatic structures and functional groups (e.g., amino, nitro, sulfonic). Inorganic contaminants include transition metal ions (e.g., Cu²⁺, Cd²⁺, Ni²⁺, Cr⁶⁺, Pb²⁺, Zn²⁺, Co²⁺) and oxyanions (e.g., IO₃[−], F[−], PO₄^{3−}) (Figure 4).

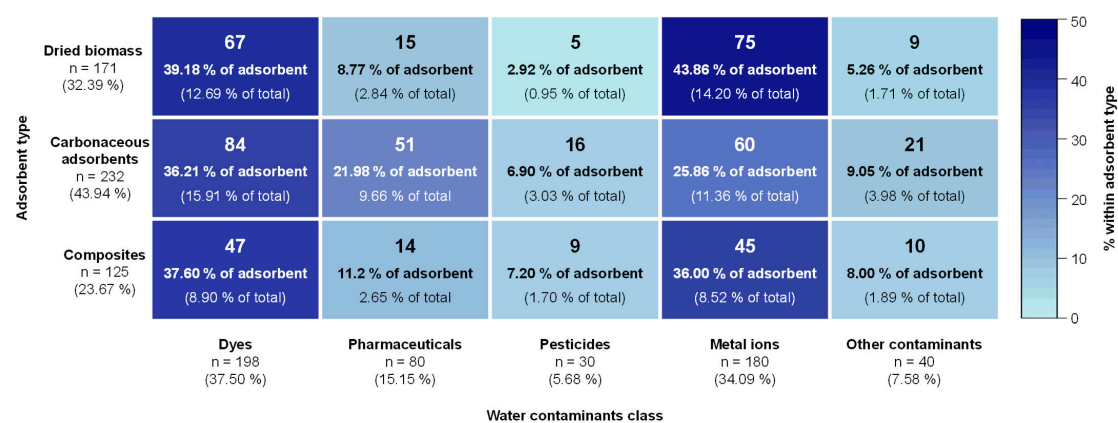


Figure 4. Heatmap on the joint and marginal distributions of adsorbent use in the reviewed literature. Each cell shows the article count (bold) and the percentage of adsorbent–pollutant combinations: values are given as the percentage within each adsorbent type and, in parentheses, as the percentage of total articles (n = 528).

As can be seen from Figure 4, the records considered for the current review are dominated by studies on dyes (37.49%) and metal ions (34.08%), while pharmaceuticals (15.15%), pesticides (5.68%) and other pollutants including oxyanions (7.57%) are less frequently investigated.

Representative molecular structures of the most frequently studied model molecules are shown in Table 1.

Table 1. Chemical structures of representative model molecules commonly encountered as water pollutants, showing the diversity of contaminants addressed in adsorption studies.

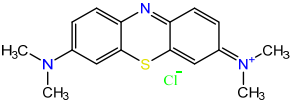
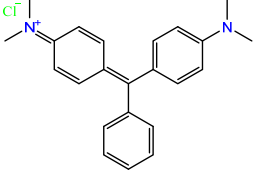
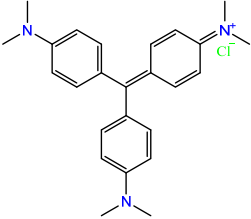
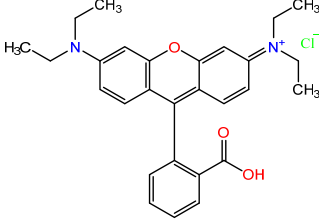
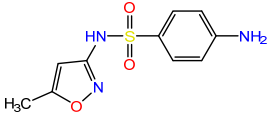
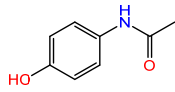
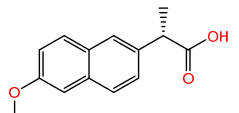
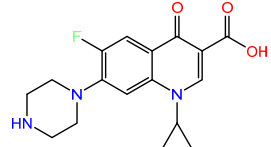
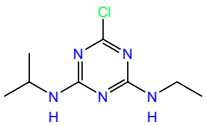
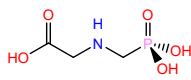
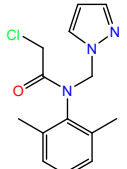
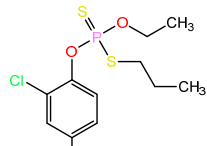
Class of Water Pollutants	Examples	
Dyes	Organic pollutants	
		
	Methylene blue	Malachite green
		
	Crystal violet	Rhodamine B

Table 1. Cont.

Class of Water Pollutants	Examples	
Pharmaceuticals		
	Sulfamethoxazole	Acetaminophen
		
	Naproxen	Ciprofloxacin
Pesticides		
	Atrazine	Glyphosate
		
	Metazachlor	Prothiofos
Inorganic pollutants		
Metal ions	Cu^{2+} , Cd^{2+} , Ni^{2+} , Cr^{6+} , Pb^{2+} , Zn^{2+} , Co^{2+}	
Other inorganic pollutants	IO_3^- , F^- , PO_4^{3-}	

3.3. Use of FW for Adsorbent Preparation

The increased consumption of fruits and their industrial processing are responsible for the generation of important quantities of waste worldwide, composed mainly of peels, seeds, kernels, pomace, and discarded biomass. Due to its high moisture content and organic load, this waste is accountable for high concerns related to its elevated fermentation potential and environmental risks, necessitating the design of effective stabilization and valorization strategies [26–28].

An effective approach in FW management involves its transformation into functional adsorbents. As the FW natural state is not favorable to direct utilization—owing to low surface area and limited stability—it must undergo specific treatments to develop the porous structures and surface functionalities required for pollutant sequestration. Table 2 summarizes representative studies, highlighting the relation between precursor types, adsorbent classes, and their respective performance against various contaminant groups.

Figure 4 pictures the classification of the 528 peer-reviewed studies by adsorbent type and target pollutant. Carbonized adsorbents dominate the dataset (43.94%), followed by dried biomass (32.39%), and composites (23.67%). Within each adsorbent category, dyes account for a consistent 36–39% of studies. Metal ions are more variable, comprising 43.86% of dried biomass studies, 36.00% of composite studies, and 25.86% of carbonaceous adsorbents studies. Pharmaceuticals are more frequently investigated using carbonaceous adsorbents (21.98%) than dried biomass (8.77%) or composites (11.2%), whereas pesticides remain marginal for all categories. These distributions reveal a strong research focus on conventional pollutants and widely used carbonaceous adsorbents, highlighting a

notable breach in the study of other emerging contaminants, particularly pharmaceuticals and pesticides.

Table 2. Condensed summary of representative FW-derived adsorbents investigated for water treatment through adsorption. Adsorbents are grouped by preparation class to facilitate the comparison of material complexity and performance. Reported values of maximum adsorption capacities are obtained under controlled laboratory conditions. The complete dataset and corresponding experimental parameters are provided in Supplementary Material S3.

FW Type	Adsorbent Class	Target Contaminant Class	Maximum Adsorption Capacity (mg/g, Range)	References
Pomegranate peels	Dried biomass	Dyes	6.83	[29]
Water chestnut, watermelon peels	Dried biomass	Dyes	294–667	[30,31]
Banana peels	Dried biomass	Dyes, pesticides	3.02–33	[32]
Orange peels	Dried biomass	Pharmaceuticals	45	[33]
Dragon fruit peels	Dried biomass	Metal ions	16.5–420	[34,35]
Watermelon rind	Dried biomass	Metal ions	230.5	[36]
Passion fruit peels	Carbonaceous adsorbents	Dyes	1.55–2.61	[37]
Watermelon rind	Carbonaceous adsorbents	Dyes	115.6	[38]
Banana peels	Carbonaceous adsorbents	Dyes	35.5	[39]
Pomegranate pomace	Carbonaceous adsorbents	Dyes	659.1	[40]
Cactus fruit peels	Carbonaceous adsorbents	Dyes	806.4	[41]
Coconut husk	Carbonaceous adsorbents	Pharmaceuticals	380–433	[42]
Mango seeds	Composite	Dyes	306.5	[43]
Lemon peels	Composite	Dyes	~24–25	[44]
Banana peels	Composite	Metal ions, pharmaceuticals	148–459	[45]

Commonly utilized precursors, such as orange, banana, mango, and pomegranate peels, are commonly used to prepare dried biomass or carbonized adsorbents (biochars, activated carbons). The adsorption capacity is highly dependent on both the FW-derived adsorbent and the target species. For instance, owing to their higher specific surface area and pore volume, activated carbons generally exhibit greater adsorption capacities than dried biomass or biochars. However, this performance advantage is accompanied by increased energy demand and chemical consumption during activation. Performance is also governed by the chemical nature of the contaminant: while dyes are efficiently removed by a wide range of adsorbents, heavy metals show strong affinity for both dried biomass and activated carbons. In contrast, pharmaceuticals are more effectively adsorbed by carbonized materials like biochars and activated carbons, which offer tailored surface chemistry. While the full 2016–2025 dataset was considered in the overall analysis presented in this review, an extended selection of studies limited to 2021–2025 (see Supplementary Material S3 [29–115]) provides a focused overview of the most recent developments. This selection includes synthesis methods, characterization techniques, adsorption conditions,

efficiencies, adsorption capacities and the kinetic and isotherm models used to describe adsorption mechanisms.

3.3.1. Dried Biomass (Unmodified and Chemically Modified)

The most straightforward method for transforming FW into adsorbents involves dehydration and mechanical size reduction. Drying temperatures ranging between ambient and 105 °C are often mentioned for effectively stabilizing the biomass by reducing moisture content and preventing fermentation. For instance, water chestnut and watermelon peels dried under sunlight or in an electric oven (at 70 °C) have demonstrated significant potential for the removal of various aqueous dyes [30,31]. Similarly, banana peels processed at 105 °C exhibited adsorption capacities of 49.2 mg/g and 164.6 mg/g for Reactive black 5 and Congo Red, respectively [116]. Other precursors, such as jackfruit peels and lime peels, have achieved removal efficiencies exceeding 90% for Remazol brilliant blue R after standard drying and grinding procedures [117]. Beyond dyes, the dried biomass of prickly pear seeds and orange peels have proven effective for the sequestration of chromium, with removal percentages of 98.24% under optimized conditions [118,119].

While unmodified dried biomass offers a low-cost, rapid solution for pollutant screening, their baseline performance is often limited by a lack of porosity and specific surface area. To overcome these constraints, chemical modification is frequently employed to introduce new functional groups or enhance existing active sites. Acidic treatment using phosphoric acid on banana and orange peel dried biomass has been shown to increase removal efficiencies for chromium ions to over 96% [120]. Alkali modification with sodium hydroxide, often in combination with crosslinking agents like ethylenediaminetetraacetic acid, has been utilized to develop mesoporous structures in orange peels, significantly improving the uptake of Trypan Blue dye and Cr^{6+} [48,121]. Furthermore, the integration of alkaline reagents and carbonates or of various acids has been reported to improve the affinity of banana, granadilla, and orange peels toward divalent metal ions such as Zn^{2+} and Ni^{2+} [55,122]. Comprehensive sequential treatments—involving both acidic and basic stages—have been applied to tangerine peels and banana stalks, resulting in materials capable of eliminating a broad spectrum of heavy metals (Cd^{2+} , Co^{2+} , Cr^{6+} , Cu^{2+} , Mn^{2+} , Ni^{2+} , Pb^{2+} , Zn^{2+}) in proportions exceeding 89% [123,124]. In specialized applications, such as the treatment of mine wastewater, modified banana peels have demonstrated exceptional selectivity, removing up to 99.99% of thorium ions and up to 70% of uranium ions [125].

Overall, FW dried biomass represents a cost-effective and accessible option for water remediation. Although they generally possess lower specific surface areas and adsorption capacities compared to thermally activated carbons, their performance can be tailored through strategic chemical functionalization. These modifications increase the density of active sites and improve the mechanical and chemical stability of the adsorbents.

3.3.2. Carbonaceous Adsorbents (Biochars and Activated Carbons)

Thermal conversion at temperatures exceeding those used for simple drying leads to the production of biochar, a carbon-rich material characterized by a developed porous structure and a variety of surface functional groups suitable for the sequestration of persistent water pollutants [126–128]. Pyrolysis parameters, particularly temperature, are decisive in determining the material's efficacy. For instance, orange peels pyrolyzed at 500 °C for 2 h yielded a biochar capable of removing over 90% of bismuth from aqueous media [64]. In the removal of tetracycline, carbonization temperature has been identified as a critical factor, alongside operational parameters such as solution pH, ionic strength, and adsorbent dosage [129]. Higher pyrolysis temperatures generally facilitate the release of volatiles (hydrogen, ammonia) and aromatic condensation, leading to increased specific surface area

and total pore volume. Research on matamba fruit shells and pomelo peels indicates that these structural improvements directly enhance adsorption capacities for contaminants like iodine and tetracyclines [130,131]. Selectivity is also a notable feature of these materials; biochar derived from banana stalks calcined at 500 °C showed high selectivity toward copper ions in multi-element solutions [132]. Furthermore, extreme thermal treatment of litchi peels (650–850 °C) has resulted in exceptional adsorption capacities for Congo red (404.4 mg/g) and malachite green (2468 mg/g) [133]. Table 1 includes other examples of biochar having various FW as raw materials.

To further enhance the performance of FW-derived carbons, activation (physical or chemical) is employed to produce activated carbon (Supplementary Material S3).

Physical activation typically involves carbonization followed by treatment with oxidizing gases like carbon dioxide or steam. Studies on citrus peels indicate that while both agents are effective in achieving 90% copper removal, carbon dioxide activation is more cost-effective [88]. Chemical activation involves the impregnation of the precursor or biochar with reagents such as sodium hydroxide, potassium hydroxide, phosphoric acid, or zinc chloride before or during carbonization. Chemical activation strategies have yielded high-performance materials tailored for specific pollutants. For example, pomegranate peels treated with sodium hydroxide and calcined at 800 °C achieved 98% carbamazepine removal [80]. Potassium hydroxide-activated date stones produced activated carbon with a surface area of 817 m²/g, demonstrating high efficacy in both batch and fixed-bed systems for levofloxacin removal, though breakthrough times were sensitive to flow rates and bed height [134]. Acidic activation using phosphoric acid, potassium hydroxide, or sodium acetate on cactus fruit peels and passion fruit shells has proven highly effective for cationic dyes (806.38 mg/g) and various heavy metals (Cr, Cu, Ni), with efficiencies reaching up to 95% [47,135]. Recent advancements also explore the integration of multiple stages, such as the thermal activation of hydrochar or the synthesis of magnetic activated carbon. Orange peel-derived hydrochar, further activated with carbon dioxide and phosphoric acid, revealed that the interplay between adsorbent porosity and the ionization state of pharmaceutical molecules (e.g., diclofenac, flurbiprofen) is fundamental to the adsorption mechanism [136]. Additionally, precursors like mango seed and pomegranate husk impregnated with zinc chloride or magnetized with iron salts have achieved the near-complete removal of methylene blue and 4-chlorophenols [137,138].

The enhancement of porosity and the surface functionality of FW-derived adsorbents through pyrolysis and activation significantly improves adsorption performance; however, elevated temperatures and activation steps are responsible for the increase in preparation costs and energy demand.

3.3.3. Composites

Even though their effectiveness in eliminating persistent compounds from aqueous media is unquestionable, adsorbents in the form of dried biomass, biochar, or activated carbon present drawbacks such as elevated production costs (especially related to the high temperatures required and to the chemical reagents implicated in the activation step) and difficulties in separation from the treated samples. These challenges can be overcome either with the help of the encapsulation of FW into friendly carriers such as biopolymers with the formation of three-dimensional structures known as gels or by modifying the various forms of FW with the final aim of obtaining various composites with the ability to remove water pollutants (Supplementary Material S3).

Hydrogels and aerogels offer superior handling and recyclability compared to fine dried biomass. A common approach involves the immobilization of FW—such as pomegranate, date pit, or orange peels—within biopolymer matrices like sodium algi-

nate or chitosan [91,92,109]. Pomegranate-alginate beads formed through calcium chloride cross-linking demonstrated stable adsorption for safranin O [92], while date pit-alginate beads achieved the near-complete removal (99.87%) of crystal violet [91].

Radiation-induced polymerization and chemical cross-linking with agents like polyacrylamide have further enhanced the mechanical strength and removal efficiencies (exceeding 90%) of dragon fruit, lemon peel, and orange peel-based hydrogels [44,109,139]. Chitosan-blended FW hydrogels have shown exceptional capacities for crystal violet and Reactive blue 4 (up to 370.37 mg/g) while maintaining performance over multiple regeneration cycles [140]. Advanced architectures, such as functionalized graphene aerogels derived from pear waste, have exhibited a tenfold increase in adsorption capacity over conventional aerogels, marking a significant leap in material efficiency [141].

In terms of composites, a multitude of papers are likewise available and were included in the present review. Functional hybridization allows for the integration of specific properties, such as magnetic susceptibility or high electrical conductivity. The magnetization of orange seed dried biomass or dragon fruit peel biopolymers with iron oxides or cobalt ferrites facilitates rapid magnetic separation from treated samples while maintaining high efficiencies for dyes, arsenite, or phenols [93,113,142]. Recent studies have also explored the growth of conductive polymers, such as polyaniline, on cellulose extracted from pomelo peels, achieving the stable sequestration of hexavalent chromium oxyanions over seven cycles [112]. Other advanced composites include the combination of orange peel-derived activated carbon with multi-walled carbon nanotubes and zinc oxide nanoparticles for methylene blue removal [94], or the modification of carbonized pomelo peels with nanoscale zero-valent iron for molybdenum remediation [143]. Furthermore, supercritical carbon dioxide drying has been used to create orange peel-silk fibroin composite foams with an adsorption capacity of 113.8 mg/g for dyes [144]. Even complex biological toxins, such as mycotoxins (aflatoxin B1, zearalenone, ochratoxin, fumonisin B1, and deoxynivalenol), can be simultaneously adsorbed using acid-treated durian peels, highlighting the versatility of these modified matrices [145].

Whereas composites often exhibit improved mechanical stability and separation efficiency (critical for continuous-flow applications and material recovery) and constitute a promising alternative toward practical deployment, reproducible synthesis, long-term stability, and regeneration cost remain subjects that should be addressed.

3.3.4. Comparative Quantitative Trends in Adsorption Performance

A comparison of maximum adsorption capacities, summarized in Table 2 and Supplementary Material S3, provides insight into the structure–property relationships of FW-derived adsorbents, as well as their practical and sustainable applicability.

Dried biomass obtained from FW generally exhibits adsorption capacities with reported values between 3.02 and 33 mg/g for banana peel dried biomass, and 6.83 mg/g for pomegranate peel dried biomass. However, certain untreated dried biomasses, such as water chestnut and watermelon peels, showed substantially higher values (294–666 mg/g), indicating that the FW intrinsic chemical composition can lead to competitive performance under favorable conditions. The dried biomass of FW is low-cost, rapidly produced, and suitable for small-scale or decentralized water treatment, but its limited surface area and porosity constrain performance in treating complex or high-concentration contaminated wastewater. Overall, simple treatments such as drying and grinding provide a baseline performance for dyes or moderately contaminated water, but additional modification is generally required for more demanding applications.

Although some dried biomasses can reach elevated adsorption capacities, FW-derived carbonaceous adsorbents generally provide more consistent and higher adsorption perfor-

mance. For biochars, the values vary from 1.55–2.61 mg/g for passion fruit peel biochar to 115.6 mg/g for watermelon rind biochar. Thermal treatment enhances porosity and stabilizes surface functional groups, improving adsorption efficiency compared to dried biomass. Biochar performance demonstrates that thermal processing alone can significantly influence adsorption behavior, although results are dependent on the retention or transformation of surface functionalities during carbonization. Activated carbons consistently show the highest adsorption capacities within comparable contaminant categories. For instance, activated carbon derived from pomegranate pomace reached 659.1 mg/g, cactus fruit peel-based activated carbon achieved 806.4 mg/g for dye adsorption and coconut husk activated carbon exhibited capacities of 380–433 mg/g for pharmaceutical compounds. These values confirm the role of activation processes in increasing surface area and creating accessible adsorption sites. However, the associated energy demand and chemical consumption reduce sustainability and increase production costs, requiring careful process optimization for large-scale deployment.

Composite materials display a broad performance spectrum. Reported adsorption capacities extend from approximately 24–25 mg/g for certain lemon peel-based composites to 459 mg/g for banana peel-derived hybrid systems applied to metal ions and pharmaceuticals. Advanced composites provide high efficiency and tailored selectivity, although their multi-step fabrication may limit large-scale deployment relative to dried biomass or biochars. This variability reflects the diversity of synthesis strategies and structural configurations employed in composite fabrication.

When considered by contaminant category, dyes frequently present the highest maximum adsorption capacities, particularly in activated carbon and composite systems. Heavy metal adsorption shows a wide range of values, with dragon fruit peel dried biomass reported between 16.5 and 420 mg/g and watermelon rind reaching 230.5 mg/g for Pb^{2+} . Pharmaceutical adsorption appears more closely associated with advanced carbonization or activation strategies, as illustrated by the contrast between orange peel dried biomass (45 mg/g for naproxen) and activated carbon derived from coconut husk (380–433 mg/g).

Based on the above aspects, it can be inferred that FW conversion into adsorbents follows a hierarchical progression from mechanical pretreatment to activation and, where required, incorporation into structured matrices. The evidence consistently indicates that the modification strategy functions as the principal design variable, whereas the specific FW precursor plays a secondary role. In its untreated form, FW is generally unsuitable for advanced applications, but targeted processing enables the development of tailored surface and structural properties. Overall, the summarized data support three general observations. First, the extent of FW modification correlates with adsorption performance: dried biomass provides baseline activity, biochars improve porosity and functional group availability, activated carbons and composites achieve the highest adsorption capacities. Second, adsorption behavior varies substantially among contaminant classes: dyes are efficiently removed across most adsorbent types, heavy metals require selective interactions with functional groups and pharmaceuticals often necessitate advanced carbonization or activation. Finally, the applied modification strategy exerts a stronger influence on performance than the choice of FW precursor, highlighting that targeted processing enables the development of tailored surface and structural properties for specific applications.

3.4. Characterization of FW-Derived Adsorbents

In interpreting differences in adsorption performance, most studies rely on a variety of advanced characterization techniques (Supplementary Material S3) such as the determination of the point of zero charge (pH_{PZC}), the measurement of zeta potential, proximate analysis, Brunauer–Emmett–Teller (BET) surface area analysis, thermogravimetric analysis

(TGA), Fourier Transform Infrared (FTIR) spectroscopy, electron microscopy and X-ray diffraction. These techniques provide the empirical basis for understanding the physical and chemical evolution of FW from raw biomass to engineered adsorbents.

Porosity development is a critical metric for FW-derived adsorbents. BET surface area analysis and nitrogen adsorption–desorption isotherms are consistently used to classify the pore architecture. For example, activated carbon derived from pine fruit residues and orange peels exhibited layered, sheet-like structures with specific surface areas exceeding 200 m²/g, confirming the presence of micro and mesopores essential for high-capacity pollutant sequestration [76,146]. Scanning Electron Microscopy (SEM) and Field Emission SEM (FESEM) complement these findings by providing visual evidence of surface morphology. Studies on orange peels and papaya skins reveal that smooth biomass surfaces transition to highly porous, rough topologies following chemical impregnation with agents like phosphoric acid or sodium hydroxide and subsequent pyrolysis [70,146]. Furthermore, SEM analysis post-adsorption often reveals surface smoothing, providing physical evidence of the pollutants retention such as tetracycline and paracetamol [76].

The surface chemistry of FW-derived adsorbents, which dictates selectivity and interaction strength, is primarily evaluated through FTIR spectroscopy. Across the reviewed literature, oxygen-containing functional groups—including carboxyl, hydroxyl, carbonyl, and aromatic rings—serve as the primary active sites for pollutant binding [70,76,146]. For modified materials, FTIR also tracks the integration of new chemical species, such as phosphorous-carbonaceous bonds after acid activation or the presence of dendritic fibrous nanosilica in apple peel-based polymers [108,146]. These insights are sustained by TGA, which assesses thermal stability, and by X-ray Diffraction (XRD), which determines the crystalline or amorphous nature of the materials, particularly in magnetic composites where patterns confirm the semi-crystalline structure of magnetite nanoparticles [76,108].

To understand the electrostatic nature of the adsorption process, measurements of pH_{PZC} and zeta potential are fundamental. These parameters allow us to predict the adsorbent's surface charge relative to the solution pH, which is crucial for the retention of ionic species like diclofenac sodium, flurbiprofen, and salicylic acid [136].

As can be seen, the above-mentioned complementary techniques form a comprehensive toolkit for the extended characterization of FW-derived adsorbents. They enable the correlation of structural and surface characteristics with adsorption performance. The multidimensional approach facilitates the optimization of synthesis parameters and pollutant removal efficiency and provides a scientific basis for the rational design of high-performance adsorbents tailored with FW as precursors for environmental remediation applications. Rather than serving as descriptive metrics, characterization parameters offer details about the adsorption behavior. Throughout the reviewed studies, increases in BET surface area and pore volume are consistently associated with higher adsorption capacities, whereas the presence and distribution of oxygen-containing functional groups primarily govern adsorption selectivity and interaction strength.

This targeted characterization approach supports rational material design, facilitates the optimization of synthesis conditions, and enables mechanistic interpretation ensuring that FW-derived adsorbents are effectively tailored for environmental remediation challenges.

3.5. Parameters Affecting the Adsorption Process

The efficiency of FW-derived adsorbents is affected by a range of interconnected variables including adsorbent dose, solution pH, contact time, initial pollutant concentration, and temperature. These factors determine the overall adsorption behavior, and their effects are closely related to the adsorbent's surface and structural properties, such

as specific surface area, pore volume, and the presence of oxygen-containing functional groups (Section 3.4), which govern the availability and strength of adsorption sites.

The adsorbent dose is one of the most impactful parameters on the adsorption. Increasing the adsorbent dose generally enhances removal efficiency by providing a greater surface area and more active sites. However, adsorption capacities often decrease at higher loadings due to site overlap and particle aggregation, which reduce surface accessibility. For example, in their research on removing lead ions from water on a tangerine peel-based adsorbent, Nag et al. observed that the removal efficiency increased up to a dosage of 2.5 g/L but declined thereafter due to adsorbent overlap and a subsequent reduction in exchangeable sites [52]. Similar dosage-dependent optimizations have been reported for pomegranate and mangosteen-derived adsorbents in iodate removal [58] and papaya peel-derived materials for methylene blue sequestration [70].

The pH of the contaminant solution is arguably the most critical parameter, as it influences both the adsorbent surface charge and the adsorbate speciation. The relationship between the solution pH and the pH_{PZC} determines electrostatic interaction. When the pH is below pH_{PZC} , the surface is protonated (positively charged), favoring the adsorption of anionic species. When pH is above pH_{PZC} , the surface is deprotonated (negatively charged), favoring the adsorption of cationic species. This is evidenced in the removal of carbendazim using apple pomace biochar, where adsorption was maximized at a neutral pH; in acidic or basic media, the molecule's dissociation state and the adsorbent's pH_{PZC} created electrostatic repulsions that hindered retention [63]. Similarly, the removal of naproxen and phosphate ions using citrus-derived adsorbents showed strong pH-dependence, with maximum uptakes reached when the target molecules' dominant forms aligned with the adsorbent's surface attraction [33,68]. For dyes like Orange G, the ultrasonic activation of peanut shells led to optimal removal at pH 5, illustrating the necessity of pH optimization for complex organic molecules [147]. The influence of pH is closely related to surface functional groups, as identified by FTIR (Section 3.4), which mediate selective interactions with charged pollutants. From a practical perspective, pH adjustment may enhance adsorption efficiency, but it introduces additional operational steps and potential chemical costs, impacting overall sustainability.

Contact time is the parameter that provides insights into the kinetics of the process and the time required to reach equilibrium. Typical FW-derived adsorbents exhibit rapid initial uptake due to the abundance of vacant surface sites, followed by a slower stage as saturation is approached. Equilibrium is generally attained within 5 to 180 min. For biochars stabilized with iron nanoparticles, such as those derived from pear peel, the majority of As(V) retention occurred within the first 5 min, with full equilibrium achieved after 2 h [148]. In more complex systems involving metal–organic frameworks cross-linked with biopolymers like chitosan or pectin, a maximum capacity of 48.50 mg/g for malachite green has been recorded after only 30 min of contact, beyond which the saturation of unoccupied sites prevents further uptake [149]. Rapid initial kinetics in orange peel-derived biochars are frequently attributed to the immediate availability of positive surface sites and high BET surface area, which facilitate the electrostatic attraction of chemical interactions with the adsorbate, as seen in the adsorption of anionic dyes like indigo carmine in orange peel biochars [150].

Another key factor in the adsorption processes is the initial concentration of the target contaminant, which provides the driving force to overcome mass transfer resistance between the solution and the adsorbent surface. At low concentrations, most active sites are readily available, resulting in rapid adsorption and high removal efficiency. As concentration increases, competition for adsorption sites intensifies, causing gradual declines in removal efficiency. However, actual adsorption capacity usually rises due to the higher

concentration gradient. Valorized banana peel wastes in the form of activated carbon or magnetic hydrogel beads show this trend clearly; the adsorption capacity for tetracycline and hexavalent chromium increases as concentrations scale from 25 to 150 mg/L [151]. Conversely, in methylene blue systems using modified grapefruit peel, the removal efficiency peaks at low concentrations (96% at 20 mg/L) but drops significantly to 50% at 200 mg/L, reflecting the stoichiometric exhaustion of active centers relative to the adsorbate load [152]. These observations highlight the importance of aligning adsorbent surface area and functional group density to the expected pollutant load.

Temperature influences the adsorption rate by altering diffusion kinetics and the viscosity of the solution. An increase in adsorption with temperature signifies an endothermic process, often associated with chemisorption or the thermal generation of new active sites, as seen in the removal of anionic and cationic dyes using banana and pomegranate peels [153]. In such cases, the analysis of the temperature impact confirms that thermal energy facilitates the interaction between the dye and the adsorbent surface. In contrast, an exothermic nature is indicated by a decrease in efficiency at higher temperatures. This was observed in citrus peel systems, where removal efficiencies for dyes declined beyond 25 °C due to decreased surface affinity [154]. In the same way, the sequestration of pharmaceuticals like acetaminophen on orange peel carbons showed a drastic reduction in efficiency from 95.5% to 30.0% when the temperature was elevated from 25 to 70 °C, identifying ambient temperature as the energetically favorable state for the interaction [75]. These effects are connected to adsorbent structure and surface chemistry. Higher temperatures may facilitate diffusion, yet excessive thermal energy can reduce interaction strength with functional groups. From an operational perspective, adsorption at ambient temperature is preferred for energy efficiency and sustainable deployment.

As can be seen, the efficacy of FW-derived adsorbents in removing pollutants from aqueous media relies on a complex interplay of factors and adsorbent characteristics. While variations of these factors influence the adsorption process, their effects are not always linear and require careful consideration. These findings highlight that while FW-derived adsorbents are versatile, their use in real polluted water systems requires a process-oriented approach to maximize both removal efficiency and economic viability.

3.6. Optimization and Modeling of the Adsorption Process

Efficient removal of persistent water pollutants using FW-derived adsorbents requires careful optimization of the operational parameters. In the studies reviewed, classical optimization has often relied on a one-factor-at-a-time approach, in which a single parameter is varied within a defined interval while others remain fixed, a process repeated iteratively until all factors are addressed. While straightforward, this algorithm assumes factor independence, which is rarely the case in complex adsorption systems where pH, dosage, initial concentration, and temperature interact (Supplementary Material S3).

To account interdependencies, Response Surface Methodology (RSM) has been widely applied. Employing a reduced number of experiments, it generates quadratic polynomial equations that map the relationship between input factors and response functions. Statistical validation, typically via Analysis of Variance, ensures the adequacy of the proposed models. Visualization through 3D response surfaces and 2D contour plots facilitates the identification of the optimal conditions for maximized response function [155,156].

Practical applications of RSM in FW valorization as precursors for adsorbent synthesis are diverse. For instance, the adsorption of brilliant green on chitosan/functionalized peach and plum stones was optimized via the Box–Behnken Design, identifying a synergy between adsorbent dose (0.051 g), pH (9.8), and contact time (46.7 min) to achieve a 93.5% removal efficiency [95]. Central Composite Design was likewise employed to optimize

lead removal (95%) on tangerine-derived iron oxide nanocomposites [157] and nickel ions retention (98.5%) on strawberry calyx waste [158]. Furthermore, multivariate optimization has elucidated the complex sensitivity of the response to factors such as temperature and contact time in the sequestration of ibuprofen on bael fruit shells [159] and Rhodamine B on date stone activated carbon [160]. These methodologies have been extended to optimize the removal of a broad spectrum of various contaminants, including sulfadiazine [161], methylene blue [162], fuchsin basic [163], and various other dyes (e.g., toluidine blue, brilliant green, crystal violet) and metal ions (lead, cadmium, nickel) on FW-derived adsorbents [44,164].

Beyond statistical modeling, machine learning (ML) techniques—specifically Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS)—have emerged as powerful tools for simulating the non-linear nature of adsorption. Constructed around the principle of human nervous system functioning, ANN is a flexible non-linear modeling tool. It maps input variables (pH, adsorbent dose, initial pollutant concentration, time, temperature, etc.) to output functions (removal efficiency, adsorption capacity, etc.) through one or more hidden neuron layers. The number of hidden layers, the number of hidden neurons, and the training rate are adjustable, their judicious modification leading to a high correspondence between the desired outputs and those of the network [165–167]. By combining neural network learning with fuzzy logic principles, ANFIS effectively handles uncertainty and imprecision while ensuring accurate input–output mapping, also useful for modeling adsorption processes suitable for water treatment. These ML methods can also minimize experimental trials, enhancing resource efficiency and sustainability in adsorption research. In studies involving copper removal via modified coconut husk biochar, a 4-2-1 ANN topology was successfully employed to forecast removal trends [87]. Other configurations, such as the 5-11-1 architecture [168] or the 14-neuron single hidden layer used [169], demonstrate the flexibility of ANN in handling diverse FW-derived adsorbents for the retention of water contaminants such as malachite green or Congo red. Additionally, the inclusion of multiple hidden layers has proven appropriate for predicting time-dependent adsorption capacities in jackfruit seed-based systems [170]. In the adsorption of 2,4-dichlorophenoxyacetic acid on *Vateria indica* biochar, a comparison between a 3-layered feed-forward ANN and an ANFIS model indicated that while both were capable of high-fidelity predictions, the ANN occasionally exhibited superior accuracy [171]. These ML applications have also been documented for sequestration of fluoride [57] and heavy metal ions [172] on FW-derived adsorbents.

As noted, although multiple papers studied for the current review commonly employ the one-factor-at-a-time method for the adsorption optimization, advanced approaches, such as RSM and ML provide more robust and efficient solutions by capturing complex interactions, reducing experimental requirements, and identifying optimal operating conditions. By improving predictive power and resource efficiency, these strategies facilitate the transition from laboratory-scale research to industrial-scale process optimization, supporting water treatment technologies using FW-derived adsorbents.

3.7. Adsorption of Water Contaminants from Single- and Multi-Component Systems

The analysis of the reviewed studies revealed that single-component adsorption systems remain fundamental for understanding FW-derived adsorbent performance. For example, watermelon rind biochar produced at 550 °C removed Methylene blue with an efficiency increasing from 35% to 81% as the dosage rose from 0.4 g to 2 g, yielding a maximum capacity of 115.61 mg/g [38]. Sodium hydroxide-modified avocado shields achieved over 96% removal of crystal violet at pH > 8, with a capacity of 179.8 mg/g [49], while orange peel exhibited an adsorption capacity of 45 mg/g for naproxen [33]. Heavy

metal removal is equally promising: hexavalent chromium ions from tannery effluents were removed by *Fusarium subglutinans* fungal biomass and *Hylocereus undatus* agro-waste adsorbent. After one hour of contact under stirring at 150 rpm, at pH 2, with an adsorbent amount of 5 g for an initial pollutant concentration of 50 mg/L, the removal efficiency was higher than 98% [34]. Watermelon rind was effective for Pb^{2+} (230.5 mg/g at pH 5) [36]. Dragon fruit peel treated with ultrasonication and sulfuric acid yielded a Cd^{2+} adsorption capacity of 24.76 mg/g in the optimized operating conditions (contact time: 60 min, adsorbent dose: 1.75 g/L, pH 6, set temperature: 30 °C) [173]. Nanocomposites, such as prickly pear biochar with magnesium ferrite, reached removal percentages above 85% for sulfadiazine [161], while magnetite-modified watermelon rinds maintained over 98% thallium removal even after five regeneration cycles [174].

A comparison of the adsorption capacities recorded for FW-derived adsorbents against those of commercial activated carbon shows that while raw FW dried biomass typically exhibits values ranging from 10% to 40% of commercial activated carbon benchmarks, FW-based carbons show significant competitiveness. Date stones treated with potassium hydroxide and citrus peels treated with phosphoric acid reported adsorption capacities for methylene blue and Pb^{2+} that reached 85–115% of those observed for standard commercial activated carbon [134,146]. This indicates that appropriate chemical functionalization and surface engineering enable FW-derived adsorbents to act as low-cost, performance-equivalent alternatives to industrial adsorbents.

While single-component studies provide essential insights, the real aqueous effluents do not constitute a controlled environment in which a single type of pollutant is present. Therefore, assessing multi-component adsorption is critical, as the presence of multiple pollutants introduces competitive effects that often reduce the process efficiency. Even though multi-component adsorption is critical for understanding the behavior of FW-derived adsorbents in realistic scenarios, only 3.4% of studies have addressed this challenge, reflecting a significant gap in the literature. In binary solutions of reactive black 5 and methylene blue using citrus peels (dried and activated with sodium hydroxide forms), methylene blue uptake was favored, with removal efficiencies of 87% (at pH 6), while reactive black 5 reached only 66.86% (at pH 2) [154]. Durian rind-based adsorbents retained 96.4% of methylene blue but only 56.3% of Rhodamine B in a binary mixture, indicating competitive adsorption when both dyes were present in the aqueous solution [175]. This antagonistic behavior was also observed for Cu^{2+} , Cr^{3+} , and Ni^{2+} adsorption on passion fruit peel [135] and for dye mixtures retention on banana, orange, and pomegranate peels, where methylene blue adsorption decreased in the presence of reactive black 5 and Remazol brilliant blue R [153]. Selective affinity is also documented for pharmaceuticals and pesticides. Pomegranate peel showed adsorption capacities of 258.98 mg/g for caffeine and 154.99 mg/g for acetaminophen; in simultaneous adsorption, acetaminophen exerted an antagonistic effect on caffeine, while caffeine did not influence acetaminophen's retention [176]. On the other hand, some systems showed enhanced selectivity: nano zero-valent iron-lemon biochar achieved a capacity of 1959.94 mg/g for methylene blue, with Congo red adsorption increasing in mixed solutions [177]. Adsorbents composed of dried banana and pomegranate peels modified with ethylenediaminetetraacetic acid retained metal ions (Cd^{2+} , Co^{2+} , Mn^{2+} , Ni^{2+}) from single and multi-component solutions. The adsorption was completed in the first 5 min. In the mixed systems, the adsorbent removed more Cd^{2+} and Ni^{2+} ions than Mn^{2+} [178]. Date pit biochar successfully removed more than 83% of a ten-pesticide mixture (excluding atrazine and dimethoate) [179]. Wider surveys confirm that adsorbents prepared from precursors such as kiwi, apple, pitahaya peels and durian rinds can retain diverse pollutants from mixtures containing carbamazepine, ibuprofen, organochlorine pesticides, heavy metal ions (Cd, Co, Hg, As), and rare-earth elements (La, Y) [146,180–186].

In summary, whereas FW-derived adsorbents reveal to be performant in single-component systems, their behavior in multi-component systems requires further exploration. Competitive adsorption effects, matrix interferences, and selectivity are insufficiently addressed in the limited number of studies identified in this direction. This critical breach between laboratory-scale investigations and real wastewater treatment scenarios restricts the direct transfer of the reported adsorption capacities to practical systems.

3.8. Adsorption Mechanism

The retention of water pollutants on FW-derived adsorbents involves the migration of the adsorbate molecules from the liquid phase to the adsorbent surface, followed by interactions with available active sites. The process is governed by multiple mechanisms elucidated through the characterization of morphology, surface functional groups, structural properties, pore structure, and surface area. Kinetic, equilibrium, and thermodynamic investigations also offer valuable information about the adsorption mechanisms. Adsorption data are usually fitted to the mathematical model, with recurrent ones given in Table 3.

Table 3. Mathematical expressions and underlying hypotheses of the main adsorption kinetics and isotherm models, along with thermodynamic parameters, used to describe contaminant removal processes via adsorption.

Model	Equation	Hypotheses	References
Kinetic models			
Pseudo-first-order	$Q_t = Q_e \cdot (1 - e^{-k_1 \cdot t})$	Adsorption occurs in heterogeneous systems Active sites are occupied through physical adsorption	[187]
Pseudo-second-order	$Q_t = \frac{k_2 \cdot Q_e^2 \cdot t}{(1 + k_2 \cdot Q_e \cdot t)}$	Interactions occur between the adsorbent and the adsorbate Active sites are occupied through chemisorption	
Isotherm models			
Langmuir	$Q_e = \frac{Q_L \cdot K_L \cdot C_e}{1 + K_L \cdot C_e}$	The adsorbent surface is homogeneous Describes monolayer uniform adsorption No interaction between the adsorbate molecules	[188]
Freundlich	$Q_e = K_F \cdot C_e^{1/n_F}$	The adsorbent surface is heterogeneous Assumes monolayer adsorption and multilayer adsorption inasmuch as chemisorption, or physisorption are the main adsorption mechanisms	
Thermodynamic			
	$\Delta G^\circ = -R \cdot T \cdot \ln K_d$ $\ln K_d = \frac{\Delta S^\circ}{R} - \frac{\Delta H^\circ}{R \cdot T}$ $\Delta G^\circ = \Delta H^\circ - T \cdot \Delta S^\circ$	$\Delta G^\circ > 0$ implies that the adsorption requires external energy $\Delta G^\circ < 0$ signifies that the adsorption is spontaneous and favored thermodynamically $\Delta S^\circ > 0$ indicates that the adsorption is based on dissociative mechanisms and that the process is random $\Delta S^\circ < 0$ indicates an associative adsorption mechanism and no important changes in the internal adsorbent structure during the retention of the target compound $\Delta H^\circ > 0$ suggests endothermic adsorption $\Delta H^\circ < 0$ suggests exothermic adsorption	[189]

Q_t —concentration on the solid phase at time t , mg/g; Q_e —adsorbent capacity at equilibrium, mg/g; k_1 —pseudo-first-order constant rate, min^{-1} ; t —contact time, min; k_2 —pseudo-second-order constant rate, $\text{g}/(\text{mg} \cdot \text{min})$; Q_L —maximum Langmuir uptake, mg/g; K_L —Langmuir constant, L/mg; K_F —Freundlich constant, $(\text{mg/g})(\text{L/mg})^{1/n_F}$; n_F —Freundlich constant, dimensionless; ΔG° —Gibbs free energy, kJ/mol; R —gas constant, $R = 8.314 \text{ J}/(\text{mol} \cdot \text{K})$; T —temperature, K; K_d —coefficient of distribution determined as ratio of the equilibrium concentration in the solid phase (C_s , mg/L) and in the solution (C_e , mg/L); ΔS° —change in entropy, J/(mol·K); ΔH° —change in enthalpy, kJ/mol.

The survey of the items included in this review identified electrostatic interactions, hydrogen bonding, π – π interactions, ion exchange, and pore-filling effects as primary mechanisms describing the retention on FW-derived adsorbents (Figure 5).

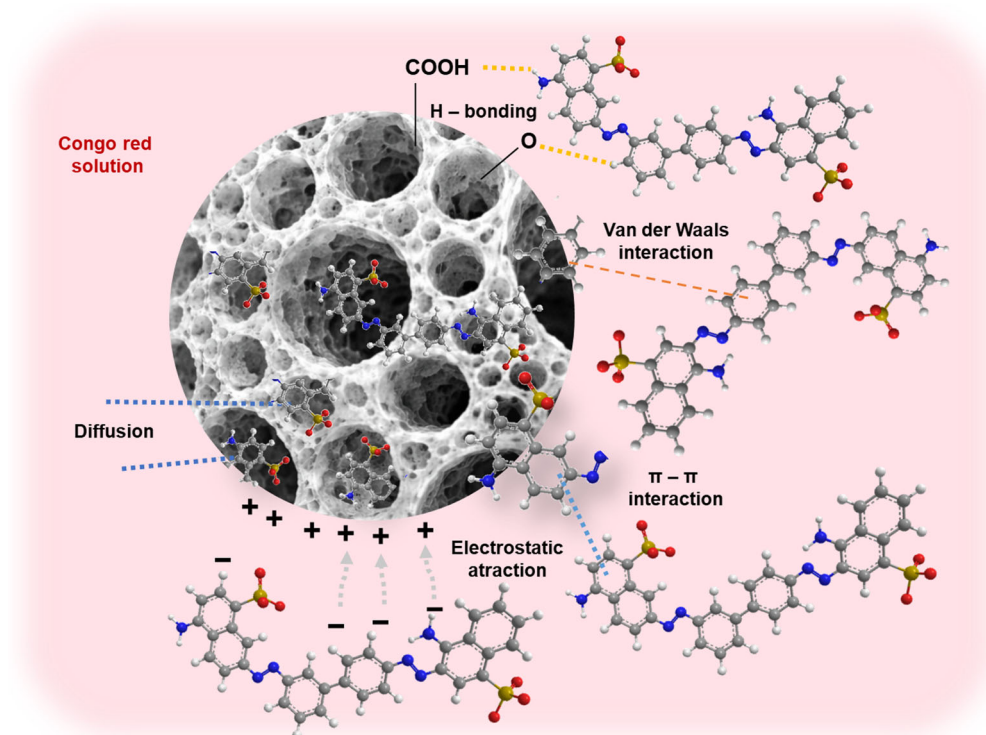


Figure 5. Schematic representation of the dominant adsorption mechanisms of a model molecule (Congo red dye) on FW-derived adsorbents, illustrating a hierarchically porous carbon framework and key physicochemical interactions, such as π - π interactions, hydrogen bonding, electrostatic attraction and pore filling.

For instance, Congo red adsorption is primarily driven by electrostatic attraction with hydrogen bonding and ion exchange mediated by OH, C=O, and S=O functional groups [101]. In hydrogel systems, such as sodium alginate/pomegranate peel composites, the removal of cationic species (e.g., Safranin O) occurred through interactions with polar negative surface groups, accompanied by van der Waals forces and π - π interactions with the lignin and cellulosic matrix [92]. More complex binding mechanisms were observed in biochars. Chestnut shell-derived biochar exhibited a combination of charge neutralization, ion exchange, hydrogen bonding, hydrophobic attractions and π - π interactions when targeting pollutants like phosphate and oxytetracycline [183]. In the same way, the retention of acid blue 193 on *Citrullus colocynthus* peels was attributed to electrostatic bonding with sulfonic acid groups and intermolecular hydrogen bonding [190].

Kinetic analyses highlight the rate-limiting steps: pseudo-first-order and, more frequently, pseudo-second-order models best describe the experimental data, indicating that chemisorption often controls the adsorption rate. It should be noted that while the pseudo-second-order kinetic model is often associated with chemisorption in the literature, several studies point that this interpretation is not always straightforward. This model may provide a good fit to experimental data primarily due to its mathematical structure rather than directly indicating chemisorption mechanisms [191–195]. Therefore, although the model can describe the kinetic behavior of adsorption systems, its fit alone should not be taken as definitive evidence of chemisorption. Confirmation through complementary analyses, such as activation energy determination or advanced characterization of the adsorbent before and after adsorption, should be considered.

At equilibrium, isotherms describe the distribution of the adsorbate molecules across the adsorbent surface, reflecting homogeneity or heterogeneity and the nature of molecular interactions. Langmuir and Freundlich models are among the most cited ones. The evalua-

tion of thermodynamic parameters discloses that in most of the adsorption systems, the retention efficiency increases with temperature, suggesting an endothermic behavior. These mechanistic trends are supported by specific experimental investigations across various FW-derived adsorbents. Adsorption of methylene blue on Brazilian berry seed-based adsorbents (carried out at initial dye concentrations ranging between 25 and 200 mg/L, at temperatures from 25 to 55 °C, for times from 5 to 180 min) follows pseudo-second-order kinetics and Langmuir models, confirming a spontaneous and endothermic pathway [196]. Adsorbents from Jeriva coconut obtained through thermal and chemical activation and used to remove methylene blue from an aqueous system (dye initial concentration between 50 and 105 mg/L, contact time of up to 180 min, and temperature between 15 and 45 °C) followed a similar behavior. The obtained results suggested that the adsorption reached equilibrium after 80 min when 93% of the pollutant was removed and that the process was described by Avrami's and Sips kinetics and isotherm models, being spontaneous, favorable, and endothermic [71]. Investigations into elephant apple fruit waste biochar for several antibiotics' removal suggested multilayer formation on the adsorbent surface. The systems were governed by chemisorption and were considered thermodynamically viable and spontaneous [62]. Peach stone biochar functionalized with phosphoric acid to remove lead, cadmium, nickel, naproxen, and chlorophenols from an aqueous environment demonstrated high versatility, achieving over 95% removal efficiency. A good correlation was established with pseudo-second-order and Langmuir models for a wide concentration range (5–500 mg/L), the adsorption being spontaneous and thermodynamically favorable [164].

Adsorption is strongly influenced by solution chemistry—especially pH and ionic strength—and is largely governed by surface sites that respond to these conditions when electrostatic interactions, hydrogen bonding, π - π interactions, and surface complexation dominate in FW-derived adsorbents. In contrast, these parameters have a lesser effect when adsorption is driven by van der Waals forces, hydrophobic interactions, or irreversible covalent bonding.

3.9. Regeneration and Reusability of FW-Derived Adsorbents

The economic viability and environmental sustainability of FW-derived adsorbents critically depend on their regeneration and reuse. The investigation conducted for this review discloses that, under suitable conditions, water pollutants can be desorbed from spent adsorbents, allowing the retention of high removal efficiencies over multiple cycles. Effective regeneration not only maintains performance but also supports circularity by reducing waste and resource consumption.

Selecting an appropriate eluent is essential to restoring active sites without compromising adsorbent structure. Mineral and organic acids are decidedly effective for desorbing dyes and heavy metals. Hydrochloric acid has demonstrated high efficiency for desorbing lead and cadmium ions from coconut mesocarp-based magnetic hybrids over three cycles [142], methylene blue from magnetized *Artocarpus heterophyllus* peels (60% recovery after five cycles) [100], and various other dyes from a magnetic orange seed-iron oxide composite (removal efficiencies higher than 90% after six cycles of adsorption-desorption) [93]. Nitric acid was successfully utilized in fixed-bed column systems using xanthate-modified apple pomace, maintaining a 76% Pb^{2+} removal efficiency after five cycles [197].

Alkaline solutions, particularly sodium hydroxide [153,198,199], were also shown to successfully desorb contaminants such as dyes and phosphate from adsorbents including dried banana, orange, and pomegranate peels; pomegranate-pomace-loaded magnetic iron oxide nanoparticles or La-Ce bimetallic nanoparticle biosorbents derived from *Citrus limon* residues.

Mild eluents such as distilled water and potassium chloride were found suitable for the adsorbent regeneration in less aggressive systems. Desorption of methylene blue and crystal violet from composites made of citrus peel dried biomass treated with acetic acid and entrapped in sodium alginate was higher than 70% in both cases, with the note that the number of adsorption cycles was twice as high for methylene blue as for crystal violet (six cycles compared to three cycles) [200].

Depending on the hydrophobic or hydrophilic nature of the contaminants, solvents are also preferred as eluents. Acetonitrile was employed to regenerate orange peel and apricot kernel adsorbents loaded with prothiofos, showing no significant adsorption capacity loss after four cycles [201]. Methanol was able to desorb short-chain per- and poly-fluoroalkyl substances from alginate-coated Ca-Fe bimetallic biochar prepared using pomelo peel and corn stover [202]. Methanol and ethanol have proven effective for the desorption of bisphenol A from pine-fruit shell-derived hydrochars [203].

Beyond traditional solvent elution, photo-Fenton oxidation has emerged as a method for unloading magnetic activated carbon. This approach achieved removal rates exceeding 80% for Rhodamine B, methyl orange, and phenol after four cycles, with efficiency sustained above 60% through six cycles [204].

Despite these encouraging results, it is noteworthy that only 17.42% of the studies included in this review report a regeneration step. The desorption of contaminants from FW-derived adsorbents is generally conducted at room temperature, using eluents with concentrations ranging from 0.1 to 0.5 M, with contact times varying between 15 min and 24 h. Both eluent concentration and contact time are critical parameters for ensuring effective regeneration. Their optimization (even though not available in the studies) may increase desorption efficiency. At the same time, concentrated eluents and extended contact times between the desorbents and adsorbents could lead to undesirable changes in adsorbent structure or entail excessive solvent use, which should be considered for scalability. Desorption is enhanced by the application of stirring to promote solute-adsorbent interactions. Occasionally, ultrasound irradiation is used to further facilitate desorption process by inducing physical disturbances that disrupt the adsorbate-adsorbent interactions. Post-desorption treatments (e.g., washing, drying), although not unanimously applied, are used for ensuring that adsorbents are properly regenerated.

In terms of structural stability, adsorbents typically retain a significant portion of their initial adsorption capacity after 3 to 6 cycles. However, performance losses are commonly observed and attributed to factors such as pore blockage (resulting from the accumulation of residual adsorbate or eluent molecules within the microporous structure), surface degradation (chemical changes to functional groups during the elution process) or incomplete desorption (contaminants' high affinity for the adsorbents prevents the full recovery of the active surface). These findings underscore the necessity of optimizing the desorption conditions and employing regeneration strategies to balance initial adsorption capacity with long-term reusability, emphasizing the critical role of regeneration efficiency in the scalability and practical deployment of FW-derived adsorbents.

4. Challenges in the Use of FW-Derived Adsorbents

The considerations discussed in this section reflect a critical synthesis of recurring trends and limitations observed across the reviewed literature.

Notwithstanding that it is considered an economic and sustainable alternative to the conventional adsorbents, the FW valorization as a precursor for the preparation of adsorbing materials useful for water decontamination is associated with several challenges.

FW compositions are complex and variable, influenced by fruit species, ripeness, climate, agricultural practices, post-harvest handling, and industrial processing. The

reliable production of adsorbents therefore requires a stable supply chain, which may be feasible near food-processing industries but challenging in regions with unorganized FW collection systems. Furthermore, the high biodegradability of FW leads to rapid microbial decomposition, compromising its suitability as an adsorption precursor if not processed promptly. Controlled storage and transport are often necessary to prevent spoilage, increasing operational costs.

Closely associated with FW variability is the challenge of manufacturing adsorbents with adequate mechanical strength and structural stability. Raw or minimally processed FW exhibit weak structural frameworks that render them inappropriate for high-pressure or continuous-flow adsorption systems. Thermal treatments (pyrolysis, carbonization) improve structural robustness; however, these processes are time and energy-consuming. Entrapping FW in polymeric matrices to produce a composite, although explored, does not always yield adsorbents mechanically appropriate for water treatment operations.

Performance toward a broad spectrum of aqueous pollutants is another drawback of FW-derived adsorbents. Although functional groups capable of interacting with water contaminants are available on the synthesized adsorbents, their density, accessibility and distribution may be insufficient for achieving high adsorption capacities or required selectivity. Many studies report chemical modification, grafting, or impregnation techniques to enhance surface area, porosity and functional group density. These treatments often involve hazardous or corrosive chemical agents, entailing higher production costs, generating secondary pollutants and potentially reducing biodegradability, which diminishes the overall sustainability advantage.

Regeneration and reusability further impact the practicality of FW-derived adsorbents. Effective water treatment necessitates materials that withstand multiple adsorption-desorption cycles with limited loss of performance. Common regeneration is achieved with eluting agents represented by aqueous solutions of common acids, bases, or salts; however, protocols are frequently suboptimal and the desorption mechanisms are insufficiently discussed. The average number of cycles remains reduced, with many FW-derived adsorbents deteriorating (structurally and chemically) after repeated use. Irreversible binding of contaminants and the degradation of FW-derived adsorbents' active sites lead to reduced adsorption capacities, increasing the operational costs and contributing to hazardous solid waste accumulation.

Another foremost downside of using FW as a precursor for adsorbent preparation concerns the difficulty of scaling laboratory findings to industrial applications. Most research on FW-derived adsorbents is performed with synthetic solutions under controlled experimental conditions, which do not capture the complexity of industrial effluents or municipal wastewater. The presence of competing ions, variable pH, dissolved organic matter and other coexisting substances can significantly alter adsorption kinetics and equilibria. Consequently, laboratory performance may not represent practical systems behavior. Large-scale operations also impose additional constraints, including fluid dynamics, mass transfer and retention time, requiring comprehensive pilot-scale validation.

These aspects have direct implications for the design and operation of water treatment systems employing FW-derived adsorbents. Beyond adsorption capacity, practical operation requires the consideration of adsorption kinetics, regeneration efficiency, mechanical stability, and operational robustness under continuous-flow conditions. Differences between batch experiments and fixed-bed or column setups, as well as the influence of real wastewater matrices, must be addressed when evaluating the feasibility of integrating FW-derived adsorbents into treatment processes.

Finally, the implementation of processes involving FW-derived adsorbents is restricted by the limited availability of techno-economic and life-cycle assessments (LCAs). Many

published studies focus on adsorption efficiency, while aspects such as energy consumption, cost–benefit considerations, carbon footprint, or environmental regulations are addressed in only a small fraction (approximately 2%) of the reviewed studies. This highlights a significant breach between laboratory-scale adsorption research and system-level sustainability evaluation. As the goal of this review was to critically analyze the available literature, we found that robust LCAs—from the raw waste collection and processing to the regeneration and disposal—are largely absent. Consequently, it remains difficult to establish if FW-derived adsorbents outperform conventional materials in terms of cost, energy, and environmental impacts. A quantitative comparison across adsorbent types was not feasible due to the limited data on these aspects, underscoring the need for future research in this area. This lack of holistic evaluation confines informed decision-making regarding their industrial deployment.

Synthesizing the above points, while the use of FW-derived adsorbents represents an attractive approach from both environmental and removal efficiency perspectives, practical implementation is restricted by technical, operational, and economic constraints. Addressing these challenges requires coordinated efforts in materials science, environmental engineering, waste management, and industrial process design. Research on standardization, process optimization, and comprehensive sustainability assessments remains essential to attain the full potential of FW-derived adsorbents for industrial water treatment.

5. Conclusions and Future Perspectives

This review highlights the potential of FW-derived adsorbents as economical and sustainable materials for the removal of dyes, pharmaceuticals, pesticides, toxins, and metal ions from water matrices. It rationalizes the impact of pivotal operational parameters affecting their performance and devotes particular attention to the optimization of adsorption processes through statistical and machine learning approaches.

Comparative analysis indicates that adsorption depends more on synthesis routes and surface functionalization applied in adsorbent preparation than on biomass origin alone, suggesting that appropriately engineered FW-derived adsorbents can achieve efficiencies competitive with conventional materials.

Despite these encouraging results, several shortcomings restrict practical implementation. Key challenges include variability in FW composition, low mechanical strength, limited selectivity for complex pollutant mixtures, incomplete regeneration and the difficulty of scaling laboratory findings to industrial applications. Environmental and economic considerations, such as life-cycle assessments, energy consumption, and cost analysis, are also insufficiently addressed in current studies.

Forthcoming investigations should focus on the following areas:

- **Material engineering:** exploring the use of mixed FW sources to increase precursor availability and improve adsorbent properties; combining FW with nanoparticles, such as metal oxides, magnetic particles, or graphene derivatives, to enhance mechanical strength, structural stability and adsorption capacity; applying pre-treatment technologies, including ultrasound and microwave-assisted processing, to accelerate manufacturing steps and optimize surface properties;
- **Mechanistic understanding:** expanding the analysis of adsorption mechanisms and compare FW-derived adsorbents to other adsorbent materials to deepen understanding of pollutant retention; investigating competitive adsorption, selectivity and matrix effects in multi-component solutions to inform practical system design;
- **Process optimization:** further development of statistical methodologies and machine learning techniques to optimize both adsorbent synthesis and adsorption processes;

establishing correlations between operational parameters (pH, dosage, contact time, temperature) and adsorption performance under dynamic conditions;

- Application to real water systems: extending investigations to complex aqueous matrices, including multi-component systems, industrial effluents and municipal wastewater; evaluating the adsorbent performance under continuous-flow conditions and pilot-scale setups to bridge laboratory and industrial applications;
- Sustainability and reusability: exploring thermal, chemical, and electrochemical techniques for adsorbent regeneration to enhance reusability and circularity; developing safe disposal or stabilization strategies for residual leachates and exhausted adsorbents to prevent secondary pollution; conducting techno-economic assessments and LCAs to evaluate environmental impact and cost-effectiveness;
- Integration with other technologies: investigation the combination of using FW-derived adsorbents with other water treatment methods (e.g., membrane filtration, photocatalysis) to improve overall system performance and operational flexibility.

Collectively, these recommendations provide a framework for advancing FW-derived adsorbents toward practical, sustainable and process-relevant applications. Future progress is likely to depend less on discovering new biomass sources and more on standardizing preparation routes, enhancing adsorption performance, and validating behavior under realistic process conditions. By addressing these challenges, FW-derived adsorbents can transition from promising laboratory-scale materials to viable alternatives for industrial water treatment.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cleantechnol8030067/s1>, Supplementary Material S1. PRISMA Protocol; Supplementary Material S2. PRISMA checklist; Supplementary Material S3. Table S1. Recent research (2021–2025) on FW-derived adsorbents for water treatment: overview of precursor types, synthesis and characterization methods, target pollutants, operational conditions, performance metrics (removal efficiency and adsorption capacity), and applied kinetic and isotherm models.

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References

1. Tabish, M.; Tabinda, A.B.; Mazhar, Z.; Yasar, A.; Ansar, J.; Wasif, I. Physical, chemical and biological treatment of textile wastewater for removal of dyes and heavy metals. *Desalin. Water Treat.* **2024**, *320*, 100842. [\[CrossRef\]](#)
2. Singh, D.; Singh, D.; Mishra, V.; Kushwaha, J.; Sengar, M.; Sinha, S.; Singh, S.; Giri, B.S. Strategies for biological treatment of waste water: A critical review. *J. Clean. Prod.* **2024**, *454*, 142266. [\[CrossRef\]](#)
3. Saleh, I.A.; Zouari, N.; Al-Ghouti, M.A. Removal of pesticides from water and wastewater: Chemical, physical and biological treatment approaches. *Environ. Technol. Innov.* **2020**, *19*, 101026. [\[CrossRef\]](#)

4. Santos, A.S.G.G.; Gorito, A.M.; Ribeiro, A.R.L.; Orge, C.A.; Pereira, M.F.R.; Soares, O.S.G.P. Innovative integrated catalytic system for enhanced water treatment: Towards a safer future for drinking water. *J. Environ. Chem. Eng.* **2026**, *14*, 121421. [\[CrossRef\]](#)
5. Fattah-alhosseini, A.; Sangarimotlagh, Z.; Chaharmahali, R.; Dikici, B.; Edalati, K. Coordination-engineered MXene-MOF hybrid membranes for sustainable water treatment: Interfaces, transport mechanisms, and environmental prospects. *J. Environ. Chem. Eng.* **2026**, *14*, 121144. [\[CrossRef\]](#)
6. Yu, W.; Lv, L.; Liu, Y.; Liu, C.; Tang, C.; Liu, Y.; Li, X.; Liu, D.; Luo, Y.; Li, J. From agricultural waste to water treatment functional materials: Performance study of nano zero-valent iron loaded on ramie biochar for persulfate-activated carbamazepine degradation. *J. Environ. Chem. Eng.* **2026**, *14*, 121029. [\[CrossRef\]](#)
7. Wang, M.; Liu, M.; Zou, H.; Liu, G. Efficient removal of Ni-EDTA complexes utilizing 3D Ni-RM electro-Fenton system. *Sep. Purif. Technol.* **2025**, *369*, 133067. [\[CrossRef\]](#)
8. Wang, M.; Song, W.; Zou, H.; Liu, G.; You, S. Synergistic Dual-Atom Cu Nanozyme for Efficient Electrocatalytic Nitrate Reduction to Ammonia. *Adv. Funct. Mater.* **2026**, *36*, 202528731. [\[CrossRef\]](#)
9. Liu, G.; He, S.; Zou, H.; You, S. Electrocatalytic hydrodechlorination of chlorophenols enhanced by hydrogen spillover on Pd-HxWO₃ catalysts. *Appl. Catal. B* **2026**, *384*, 126220. [\[CrossRef\]](#)
10. Dhaouadi, F.; Aouaini, F.; Basha, B.; Bonilla-Petriciolet, A.; Georgin, J.; Ben Lamine, A. Evaluation and analysis of the adsorption mechanism of three emerging pharmaceutical pollutants on a phosphorised carbon-based adsorbent: Application of advanced analytical models to overcome the limitation of classical models. *Heliyon* **2024**, *10*, e34788. [\[CrossRef\]](#)
11. Lladó, J.; López, F.; Rossell, J.M.; Lao-Luque, C.; Gil, R.R.; Fuente, E.; Ruiz, B. Multivariate analysis of pharmaceutical pollutants adsorption in aqueous media with tailored waste-based carbonaceous adsorbent materials and commercial activated carbons. *Sustain. Chem. Pharm.* **2024**, *38*, 101453. [\[CrossRef\]](#)
12. Ashebir, H.; Nure, J.F.; Worku, A.; Msagati, T.A.M. Prosopis juliflora biochar for adsorption of sulfamethoxazole and ciprofloxacin from pharmaceutical wastewater. *Desalin. Water Treat.* **2024**, *320*, 100691. [\[CrossRef\]](#)
13. Barooah, P.; Mushahary, N.; Das, B.; Basumatary, S. Waste biomass-based graphene oxide decorated with ternary metal oxide (MnO-NiO-ZnO) composite for adsorption of methylene blue dye. *Clean. Water.* **2024**, *2*, 100049. [\[CrossRef\]](#)
14. Kumar, N.; Kumar, V.; Garg, V.K. Development of iron-based metal-organic frameworks for the efficient removal of industrial dye: Effect of ligands on morphological and adsorption parameters. *J. Solid State Chem.* **2025**, *347*, 125337. [\[CrossRef\]](#)
15. Behera, S.; Barik, P.; Chandra Behera, B.; Thatoi, H. Adsorption of basic dyes from aqueous solutions using nano-lignin synthesized from waste agricultural rice straw. *Waste Manag. Bull.* **2024**, *2*, 136–144. [\[CrossRef\]](#)
16. Sanz-Santos, E.; Gutiérrez-Sánchez, P. Multicomponent and continuous adsorption of neonicotinoid pesticides identified in the EU Watch Lists onto mesoporous and biogenic activated carbon. *Sep. Purif. Technol.* **2024**, *346*, 127514. [\[CrossRef\]](#)
17. Naboulsi, A.; Bouzid, T.; Grich, A.; Regti, A.; El Himri, M.; El Haddad, M. Understanding the column and batch adsorption mechanism of pesticide 2,4,5-T utilizing alginate-biomass hydrogel capsule: A computational and economic investigation. *Int. J. Biol. Macromol.* **2024**, *275*, 133762. [\[CrossRef\]](#)
18. Almahri, A.; Abou-Melha, K.S.; Katouah, H.A.; Al-bonayan, A.M.; Saad, F.A.; El-Desouky, M.G.; El-Bindary, A.A. Adsorption and removal of the harmful pesticide 2,4-dichlorophenylacetic acid from an aqueous environment via coffee waste biochar: Synthesis, characterization, adsorption study and optimization via Box-Behnken design. *J. Mol. Struct.* **2023**, *1293*, 136238. [\[CrossRef\]](#)
19. Zhao, D.; Chen, H.; Zhao, Q.; Qi, W.; Liu, Y.; Tian, Y. Recycling corn stalks as an effective biosorbent for heavy metal removal from wastewater: Investigation on the adsorption performance and mechanism. *Environ. Technol. Innov.* **2025**, *38*, 104140. [\[CrossRef\]](#)
20. Truong, T.T.; Vuong, T.X.; Chu, T.H.H.; Diep, T.H.T.; Ta, H.C.; Hoang, L.P.; Pham, T.D. Synthesis of novel hydrochar from lemongrass distillation waste and its application in individual and simultaneous adsorption of a mixture of heavy metal ions. *J. Water Process Eng.* **2025**, *71*, 107402. [\[CrossRef\]](#)
21. Nguyen, V.D.; Nguyen, T.P.; Vu, A.-T. Chemical modification of lettuce leaves using NaOH and EDTA: A brilliant biosorbent for the adsorption of heavy metal ions from aqueous solution. *J. Water Process Eng.* **2025**, *71*, 107202. [\[CrossRef\]](#)
22. Ton-That, L.; Nguyen, T.-P.-T.; Duong, B.-N.; Nguyen, D.-K.; Nguyen, N.-A.; Ho, T.H.; Dinh, V.-P. Insights into Pb (II) adsorption mechanisms using jackfruit peel biochar activated by a hydrothermal method toward heavy metal removal from wastewater. *Biochem. Eng. J.* **2024**, *212*, 109525. [\[CrossRef\]](#)
23. Argun, M.E.; Argun, M.S.; Ates, H. Zero waste principle for the fruit processing industry: Recovery, advanced conversion and revalorization approaches. *J. Water Process Eng.* **2025**, *71*, 107243. [\[CrossRef\]](#)
24. Ávila, F.G.; Cabrera-Sumba, J.; Valdez-Pilataxi, S.; Villalta-Chungata, J.; Valdiviezo-Gonzales, L.; Alegria-Arnedo, C. Removal of heavy metals in industrial wastewater using adsorption technology: Efficiency and influencing factors. *Clean. Eng. Technol.* **2025**, *24*, 100879. [\[CrossRef\]](#)
25. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *J. Clin. Epidemiol.* **2021**, *134*, 178–189. [\[CrossRef\]](#) [\[PubMed\]](#)

26. Roy, P.; Graceffa, V. From waste to therapeutics: Extraction methodologies and biological properties of bioactive compounds from fruit and vegetable waste. *Food Biosci.* **2024**, *62*, 105389. [\[CrossRef\]](#)
27. Mgeni, S.T.; Mero, H.R.; Mtashobya, L.A.; Emmanuel, J.K. The prospect of fruit wastes in bioethanol production: A review. *Heliyon* **2024**, *10*, e38776. [\[CrossRef\]](#)
28. Khan, R.; Anwar, F.; Ghazali, F.M.; Mahyudin, N.A. Valorization of waste: Innovative techniques for extracting bioactive compounds from fruit and vegetable peels—A comprehensive review. *Innov. Food Sci. Emerg. Technol.* **2024**, *97*, 103828. [\[CrossRef\]](#)
29. El-Dein, W.A.S.; Mahdi, Z.A.; Lotfy, H.R. A comprehensive study on pomegranate (*Punicagranatum*) peels as a low-cost biosorbent: Adsorption mechanisms, application, regeneration, and cost analysis. *Environ. Monit. Assess.* **2025**, *197*, 229. [\[CrossRef\]](#)
30. Rehman, R.; Hussain, M.S.; Samin, G.; Jahangir, M.M.; Dar, A.; Al-thagafi, Z.T.; Alsantali, R.I.; Al-Abbad, E.A.; Akram, M. Effective application of citric acid treated *Trapa natans* and *Citrullus lanatus* lignocellulosic macromolecules for adsorptive remediation of acid Violet-7 dye. *Int. J. Biol. Macromol.* **2024**, *256*, 128285. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Rehman, R.; Hussain, M.S.; Abidin, A.; Ghfar, A.A.; Hossain, N.; Akram, M.; Dar, A. Exploring feasibility of citric acid infused lignocellulosic waste derived from chestnut and water melon peels for phytofiltration of Eosin yellow dye from water. *Int. J. Biol. Macromol.* **2024**, *276*, 133878. [\[CrossRef\]](#)
32. Farias, K.C.S.; Guimarães, R.C.A.; Oliveira, K.R.W.; Nazário, C.E.D.; Ferencz, J.A.P.; Wender, H. Banana peel powder biosorbent for removal of hazardous organic pollutants from wastewater. *Toxics* **2023**, *11*, 664. [\[CrossRef\]](#)
33. Jmai, S.; Jmai, L.; Guiza, S.; Lamari, H.; Launay, F.; Karoui, S.; Bagane, M. Removal of naproxen from aqueous solutions using eco-friendly bio-adsorbent prepared from orange peels. *Water Air Soil Pollut.* **2024**, *235*, 321. [\[CrossRef\]](#)
34. Latha, A.; Ganesan, R.; Venkatesan, G.; Baraneedharan, P. Removal of toxic heavy metal ion from tannery effluent by using *Fusarium subglutinans* and *Hylocereus undatus*. *Desalin. Water Treat.* **2023**, *312*, 70–78. [\[CrossRef\]](#)
35. Saravanan, A.; Senthil Kumar, P.; Varjani, S.; Karishma, S.; Jeevanantham, S.; Yaashikaa, P.R. Effective removal of Cr(VI) ions from synthetic solution using mixed biomasses: Kinetic, equilibrium and thermodynamic study. *J. Water Process Eng.* **2021**, *40*, 101905. [\[CrossRef\]](#)
36. Wang, Q.; Wang, Y.; Tang, J.; Yang, Z.; Zhang, L.; Huang, X. New insights into the interactions between Pb(II) and fruit waste biosorbent. *Chemosphere* **2022**, *303*, 135048. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Cabral, L.L.; Bottini, R.C.R.; Gonçalves, A.J.; Junior, M.M.; Rizzo-Domingues, R.C.P.; Lenzi, M.K.; Nagalli, A.; Passig, F.H.; Dos Santos, P.M.; Carvalho, K.Q. Food dye adsorption in single and ternary systems by the novel passion fruit peel biochar adsorbent. *Food Chem.* **2025**, *464*, 141592. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Shukla, S.; Khan, R.; Srivastava, M.M.; Zahmatkesh, S. Valorization of waste watermelon rinds as a bio-adsorbent for efficient removal of methylene blue dye from aqueous solutions. *Appl. Biochem. Biotechnol.* **2024**, *196*, 2534–2548. [\[CrossRef\]](#)
39. Daffalla, S.; Taha, A.; Da'na, E.; El-Aassar, M.R. Sustainable banana-waste-derived biosorbent for Congo red removal from aqueous solutions: Kinetics, equilibrium, and breakthrough studies. *Water* **2024**, *16*, 1449. [\[CrossRef\]](#)
40. Benmahdi, F.; Khettaf, S.; Khelali, A.; Kolli, M. High-quality mesoporous adsorbent derived from pomegranate pomace for efficient removal of azo dye from textile wastewater: Influencing factors, reusability, and mechanism studies. *J. Indian Chem. Soc.* **2024**, *101*, 101320. [\[CrossRef\]](#)
41. Akkari, I.; Graba, Z.; Bezzi, N.; Kaci, M.M.; Ait Merzeg, F.A.; Baït, N.; Ferhati, A.; Dotto, G.L.; Benguerba, Y. Effective removal of cationic dye on activated carbon made from cactus fruit peels: A combined experimental and theoretical study. *Environ. Sci. Pollut. Res.* **2023**, *30*, 3027–3044. [\[CrossRef\]](#)
42. Sarkar, S.; Das, P.; Chakraborty, P.; Bhowal, A. Developing Novel High-Performance Activated Carbon from Coconut Husk: Optimization Strategies for Synthesis and Applications in Pharmaceuticals Removal from Aqueous Solution. *Water Air Soil Pollut.* **2025**, *236*, 899. [\[CrossRef\]](#)
43. Abdulhameed, A.S.; Abdullah, S.; Al-Masud, A.A.; Al Omari, R.H.; Abualhaija, M.; Algburi, S. Production of sustainable adsorbent of crosslinked chitosan-oxalate and modified mango (*Mangifera indica* L.) seed for highly efficient adsorption of crystal violet dye: Water treatment and biomass valorization. *Biomass Bioenergy* **2025**, *199*, 107889. [\[CrossRef\]](#)
44. Das, T.; Patel, D.K. Efficient removal of cationic dyes using lemon peel-chitosan hydrogel composite: RSM-CCD optimization and adsorption studies. *Int. J. Biol. Macromol.* **2024**, *275*, 133561. [\[CrossRef\]](#)
45. Hu, Z.T.; Ding, Y.; Shao, Y.; Cai, L.; Jin, Z.Y.; Liu, Z.; Zhao, J.; Li, F.; Pan, Z.; Li, X.; et al. Banana peel biochar with nanoflake-assembled structure for cross contamination treatment in water: Interaction behaviors between lead and tetracycline. *Chem. Eng. J.* **2021**, *420*, 129807. [\[CrossRef\]](#)
46. Carvalho, C.M.D.; Sanches-Neto, F.O.; Carvalho-Silva, V.H.; Ascheri, D.P.R.; Signini, R. Response surface and DFT protocols for improvement of the adsorption process of lignocellulosic-based biomass for the removal of basic dyes. *Int. J. Biol. Macromol.* **2024**, *275*, 133208. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Akkari, I.; Graba, Z.; Bezzi, N.; Ait Merzeg, F.A.; Baït, N.; Ferhati, A.; Kaci, M.M. Biosorption of Basic Red 46 using raw cactus fruit peels: Equilibrium, kinetic and thermodynamic studies. *Biomass Convers. Biorefin.* **2024**, *14*, 1825–1836. [\[CrossRef\]](#)

48. Eddy, N.O.; Garg, R.; Garg, R.; Aikoye, A.O.; Ita, B.I. Waste to resource recovery: Mesoporous adsorbent from orange peel for the removal of trypan blue dye from aqueous solution. *Biomass Convers. Biorefin.* **2023**, *13*, 13493–13511. [\[CrossRef\]](#)
49. Haki, M.A.; Imgharn, A.; Aarab, N.; Hsini, A.; Essekrei, A.; Laab, M.; El Jazouli, H.; Elamine, M.; Lakhmiri, R.; Albourine, A. Efficient removal of crystal violet dye from aqueous solutions using sodium hydroxidemodified avocado shells: Kinetics and isotherms modeling. *Water Sci. Technol.* **2022**, *85*, 433–448. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Wei, W.; Shang, N.; Zhang, X.; Liu, W.; Zhang, T.; Wu, M. A green 3-step combined modification for the preparation of biomass sorbent from waste chestnut thorns shell to efficient removal of methylene blue. *Bioresour. Technol.* **2022**, *360*, 127593. [\[CrossRef\]](#)
51. Raji, Z.; Maleka, R.; Karim, A.; Karam, A.; Aider, M.; Khalloufi, S. Biosorption of lead from water using fruit and vegetable peels: Characteristics, adsorption kinetics, and isotherms. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 15775–15790. [\[CrossRef\]](#)
52. Nag, S.; Bhowmik, S.; Bar, N.; Das, S.K. Biosorption of Pb(II) from aqueous solution by citrus reticulate: Adsorption studies, and modeling. *Int. J. Phytoremediation* **2024**, *26*, 1996–2009. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Khalfaoui, A.; Benalia, A.; Selama, Z.; Hammoud, A.; Derbal, K.; Panico, A.; Pizzi, A. Removal of chromium (VI) from water using orange peel as the biosorbent: Experimental, modeling, and kinetic studies on adsorption isotherms and chemical structure. *Water* **2024**, *16*, 742. [\[CrossRef\]](#)
54. Hadjar, H.; Bachiller-Baeza, B.; Labied, R. New low-cost agricultural biosorbent from algerian melon “*Cucumis melo*” peels for remediation of water Ni (II) pollution. *Water Air Soil Pollut.* **2024**, *235*, 421. [\[CrossRef\]](#)
55. Castro, D.; Rosas-Laverde, N.M.; Aldás, M.B.; Almeida-Naranjo, C.E.; Guerrero, V.H.; Pruna, A.I. Chemical modification of agro-industrial waste-based bioadsorbents for enhanced removal of Zn(II) ions from aqueous solutions. *Materials* **2021**, *14*, 2134. [\[CrossRef\]](#)
56. Dinh, V.P.; Xuan, T.D.; Hung, N.Q.; Luu, T.T.; Do, T.T.T.; Nguyen, T.D.; Nguyen, V.D.; Anh, T.T.K.; Tran, N.Q. Primary biosorption mechanism of lead (II) and cadmium (II) cations from aqueous solution by pomelo (*Citrus maxima*) fruit peels. *Environ. Sci. Pollut. Res.* **2021**, *28*, 63504–63515. [\[CrossRef\]](#)
57. Jena, D.; Bej, A.K.; Giri, A.K.; Mishra, P.C. Amino-functionalized novel biosorbent for effective removal of fluoride from water: Process optimization using artificial neural network and mechanistic insights. *Environ. Sci. Pollut. Res.* **2024**, *31*, 29415–29433. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Phanthuwongpakdee, J.; Babel, S. Unraveling the mechanism of iodate adsorption by anthocyanin-rich fruit waste as green adsorbents for Applications of radioactive iodine remediation in water environment. *Environ. Res.* **2024**, *250*, 118502. [\[CrossRef\]](#)
59. Nguyen, N.T.; Chen, P.R.; Ye, R.H.; Chuang, K.J.; Chang, C.T.; Hong, G.B. Optimization of extraction conditions from gac fruit and utilization of peel-derived biochar for crystal violet dye removal. *Molecules* **2024**, *29*, 3435. [\[CrossRef\]](#)
60. Abdel Azim, E.; Samy, M.; Hanafy, M.; Mahanna, H. Novel mint-stalks derived biochar for the adsorption of methylene blue dye: Effect of operating parameters, adsorption mechanism, kinetics, isotherms, and thermodynamics. *J. Environ. Manag.* **2024**, *357*, 120738. [\[CrossRef\]](#)
61. Nguyen, T.K.T.; Nguyen, T.B.; Chen, C.W.; Chen, W.H.; Bui, X.T.; Lam, S.S.; Dong, C.D. Boosting acetaminophen degradation in water by peracetic acid activation: A novel approach using chestnut shell-derived biochar at varied pyrolysis temperatures. *Environ. Res.* **2024**, *252*, 119143. [\[CrossRef\]](#)
62. Gautam, N.; Das, G. Adsorption of antiviral and antibiotics by recyclable biochar derived from *Dillenia indica*: Impact of pyrolysis temperature and duration. *Colloid Surf. A Physicochem. Eng. Asp.* **2024**, *703*, 135265. [\[CrossRef\]](#)
63. Rasool, S.; Rasool, T.; Gani, K.M. Understanding the carbendazim adsorption from water using biochar derived from apple pomace and industrial wastewater sludge: Experimental and DFT approaches. *Environ. Sci. Pollut. Res.* **2024**, *31*, 47818–47835. [\[CrossRef\]](#)
64. Kareem, A.A.; Liao, Y.L.; Yu, Y.Q.; Ning, N.; Guo, S.S.; Song, Q.Y.; Li, J.L.; Yang, J.Y. Removal of bismuth from water by orange peel biochar. *Water Air Soil Pollut.* **2024**, *235*, 190. [\[CrossRef\]](#)
65. Chaudhary, H.; Dinakaran, J.; Notup, T.; Vikram, K.; Rao, K.S. Comparison of adsorption performance of biochar derived from urban biowaste materials for removal of heavy metals. *Environ. Manag.* **2024**, *73*, 408–424. [\[CrossRef\]](#)
66. Yuan, Z.; Sun, X.; Hua, J.; Zhu, Y.; Yuan, J.; Qiu, F. Upcycling watermelon peel waste into a sustainable environment-friendly biochar for assessment of effective adsorption property. *Arab. J. Sci. Eng.* **2023**, *48*, 9035–9045. [\[CrossRef\]](#)
67. Chen, Y.; Yang, J.; Abbas, A. Enhanced chromium (VI) adsorption onto waste pomegranate-peel-derived biochar for wastewater treatment: Performance and mechanism. *Toxics* **2023**, *11*, 440. [\[CrossRef\]](#)
68. Saleh, M.; Alterkaoui, A.; Ozdemir, N.C.; Arslan, H.; Bilici, Z.; Dizge, N. Adsorption of phosphate ions and reactive red 180 from aqueous solution using thermally activated lemon peels waste. *Int. J. Environ. Sci. Technol.* **2024**, *21*, 1683–1696. [\[CrossRef\]](#)
69. de Paula Filho, F.J.; Teixeira, Y.N.; Bacurau, V.P.; Zhong Fan, A.; Menezes, J.M.C.; Oliveira, T.M.B.F.; Teixeira, R.N.P.; Coutinho, H.D.M.; do Nascimento, R.F. Adsorption of phosphate in aqueous solution by ash from the fruit peel of *Caryocar coriaceum* Wittm: Adsorption characteristics and behavior. *Environ. Sci. Pollut. Res.* **2024**, *31*, 40117–40132. [\[CrossRef\]](#)
70. Waghmare, C.; Ghodmare, S.; Ansari, K.; Dehghani, M.H.; Amir Khan, M.; Hasan, M.A.; Islam, S.; Khan, N.A.; Zahmatkesh, S. Experimental investigation of H₃PO₄ activated papaya peels for methylene blue dye removal from aqueous solution: Evaluation

- on optimization, kinetics, isotherm, thermodynamics, and reusability studies. *J. Environ. Manag.* **2023**, *345*, 118815. [[CrossRef](#)] [[PubMed](#)]
71. Tochetto, G.A.; da Silva, T.C.; Bampi, J.; Moreira, R.d.F.P.M.; da Luz, C.; Pasquali, G.D.L.; Dervanoski, A. Conversion of *Syagrus romanzoffiana* into high-efficiency biosorbent for dye removal from synthetic and real textile effluent. *Water Air Soil Pollut.* **2022**, *233*, 252. [[CrossRef](#)]
 72. Singh, S.; Gupta, H.; Dhiman, S.; Sahu, N.K. Decontamination of cationic dye brilliant green from the aqueous media. *Appl. Water Sci.* **2022**, *12*, 61. [[CrossRef](#)]
 73. Giraldo, S.; Robles, I.; Godínez, L.A.; Acelas, N.; Flórez, E. Experimental and theoretical insights on methylene blue removal from wastewater using an adsorbent obtained from the residues of the orange industry. *Molecules* **2021**, *26*, 4555. [[CrossRef](#)]
 74. Lawtae, P.; Tangsathitkulchai, C. The use of high surface area mesoporous-activated carbon from longan seed biomass for increasing capacity and kinetics of methylene blue adsorption from aqueous solution. *Molecules* **2021**, *26*, 6521. [[CrossRef](#)]
 75. Saied, M.E.; Shaban, S.A.; Mostafa, M.S.; Naga, A.O.A.E. Efficient adsorption of acetaminophen from the aqueous phase using low-cost and renewable adsorbent derived from orange peels. *Biomass Convers. Biorefin.* **2024**, *14*, 2155–2172. [[CrossRef](#)]
 76. Hashemzadeh, F.; Ariannezhad, M.; Derakhshandeh, S.H. Sustainable removal of tetracycline and paracetamol from water using magnetic activated carbon derived from pine fruit waste. *Sci. Rep.* **2024**, *14*, 16346. [[CrossRef](#)]
 77. Solmaz, A.; Karta, M.; Depci, T.; Turna, T.; Sari, Z.A. Preparation and characterization of activated carbons from lemon pulp for oxytetracycline removal. *Environ. Monit. Assess.* **2023**, *195*, 797. [[CrossRef](#)]
 78. Santos, R.K.S.; Nascimento, B.F.; de Araújo, C.M.B.; Cavalcanti, J.V.F.L.; Bruckmann, F.S.; Rhoden, C.R.B.; Dotto, G.L.; Oliveira, M.L.S.; Silva, L.F.O.; Motta Sobrinho, M.A. Removal of chloroquine from the aqueous solution by adsorption onto açai-based biochars: Kinetics, thermodynamics, and phytotoxicity. *J. Mol. Liq.* **2023**, *383*, 122162. [[CrossRef](#)]
 79. Franco, D.S.P.; Georgin, J.; Ramos, C.G.; Eljaiek, S.M.; Badillo, D.R.; de Oliveira, A.H.P.; Allasia, D.; Meili, L. The synthesis and evaluation of porous carbon material from corozo fruit (*Bactris guineensis*) for efficient propranolol hydrochloride adsorption. *Molecules* **2023**, *28*, 5232. [[CrossRef](#)] [[PubMed](#)]
 80. Al-Ghoul, N.E.; Albarghouti, G.A.; Qandeel, R.G. Activated carbon-based pomegranate peels as an efficient removal method for carbamazepine. *Environ. Monit. Assess.* **2023**, *195*, 821. [[CrossRef](#)]
 81. Magesh, N.; Annam Renita, A.A.; Ramasamy, R.; Harirajan, N.; Santhosh, A. Adsorption behavior of fluoro-quinolone (ciprofloxacin) using zinc oxide impregnated activated carbon prepared from jack fruit peel: Kinetics and isotherm studies. *Chemosphere* **2022**, *290*, 133227. [[CrossRef](#)] [[PubMed](#)]
 82. Hamadeen, H.M.; Elkhatib, E.A. New nanostructured activated biochar for effective removal of antibiotic ciprofloxacin from wastewater: Adsorption dynamics and mechanisms. *Environ. Res.* **2022**, *210*, 112929. [[CrossRef](#)]
 83. Franco, D.S.P.; da Boit Martinello, K.; Georgin, J.; Netto, M.S.; Foletto, E.L.; Picilli, D.G.A.; Silva, L.F.O.; dos Reis, G.S.; Dotto, G.L. Application of biowaste generated by the production chain of pitaya fruit (*Hylocereus undatus*) as an efficient adsorbent for removal of naproxen in water. *Environ. Sci. Pollut. Res.* **2022**, *29*, 39754–39767. [[CrossRef](#)]
 84. Aziz, A.; Yusop, M.F.M.; Ahmad, M.A. Removal of bisphenol S from aqueous solution using activated carbon derived from rambutan peel via microwave irradiation technique. *Sains Malays.* **2022**, *51*, 3967–3980. [[CrossRef](#)]
 85. Kang, J.; Bai, X.; Leng, J.; Lou, Y.; Chen, D.; Jiang, L.; Wang, J. Magnesium bicarbonate–walnut shell dual-template synthesis of multifunctional layered porous carbon for enhanced adsorption of aqueous chlorinated organic compounds. *Int. J. Mol. Sci.* **2024**, *25*, 1761. [[CrossRef](#)] [[PubMed](#)]
 86. Taheri, E.; Fatehizadeh, A.; Lima, E.C.; Rezakazemi, M. High surface area acid-treated biochar from pomegranate husk for 2,4-dichlorophenol adsorption from aqueous solution. *Chemosphere* **2022**, *295*, 133850. [[CrossRef](#)] [[PubMed](#)]
 87. Yadav, K.; Raphi, M.; Jagadevan, S. Adsorption of copper(II) on chemically modified biochar: A single-stage batch adsorber design and predictive modeling through artificial neural network. *Biomass Convers. Biorefin.* **2024**, *14*, 6011–6026. [[CrossRef](#)]
 88. da Silva, M.D.; Schnorr, C.; Lütke, S.F.; Felipe Oliveira Silva, L.F.O.; Manera, C.; Perondi, D.; Godinho, M.; Carvalho Collazzo, G.C.; Dotto, G.L. Citrus fruit residues as alternative precursors to developing H₂O and CO₂ activated carbons and its application for Cu(II) adsorption. *Environ. Sci. Pollut. Res.* **2023**, *30*, 63661–63677. [[CrossRef](#)]
 89. Khalil, K.M.S.; Elhamdy, W.A.; Elsamahy, A.A. Biomass derived P–doped activated carbon as nanostructured mesoporous adsorbent for chromium(VI) pollutants with pronounced functional efficiency and recyclability. *Colloid Surf. A Physicochem. Eng. Asp.* **2022**, *641*, 128553. [[CrossRef](#)]
 90. Rawat, S.; Ahammed, M.M. Clay–moringa seedcake composite for removal of cationic and anionic dyes. *Chemosphere* **2024**, *350*, 141083. [[CrossRef](#)]
 91. Mokhtar, A.; Abdelkrim, S.; Hachemaoui, M.; Boukoussa, B.; Chaibi, W.; Sardi, A.; Djelad, A.; Sassi, M.; Ismail, I.; Iqbal, J.; et al. Removal of crystal violet dye using a three-dimensional network of date pits powder/sodium alginate hydrogel beads: Experimental optimization and DFT calculation. *Int. J. Biol. Macromol.* **2023**, *251*, 126270. [[CrossRef](#)]
 92. Abbaz, A.; Arris, S.; Viscusi, G.; Ayat, A.; Aissaoui, H.; Boumezough, Y. Adsorption of Safranin O dye by alginate/pomegranate peels beads: Kinetic, isotherm and thermodynamic studies. *Gels* **2023**, *9*, 916. [[CrossRef](#)] [[PubMed](#)]

93. Foroutan, R.; Peighambaroust, S.J.; Ghojavand, S.; Foroughi, M.; Ahmadi, A.; Bahador, F.; Ramavandi, B. Development of a magnetic orange seed/Fe₃O₄ composite for the removal of methylene blue and crystal violet from aqueous media. *Biomass Convers. Biorefin.* **2024**, *14*, 25685–25700. [\[CrossRef\]](#)
94. Licona-Aguilar, A.I.; Torres-Huerta, A.M.; Domínguez-Crespo, M.A.; Negrete-Rodríguez, M.L.X.; Conde-Barajas, E.; Brachetti-Sibaja, S.B.; Rodríguez-Salazar, A.E. Valorization of agroindustrial orange peel waste during the optimization of activated carbon–multiwalled carbon nanotubes–zinc oxide composites used in the removal of methylene blue in wastewater. *Chem. Eng. J.* **2024**, *492*, 152102. [\[CrossRef\]](#)
95. Khan, M.K.A.; Abdulhameed, A.S.; Alshahrani, H.; Algburi, S. Chitosan/functionalized fruit stones as a highly efficient adsorbent biomaterial for adsorption of brilliant green dye: Comprehensive characterization and statistical optimization. *Int. J. Biol. Macromol.* **2024**, *263*, 130465. [\[CrossRef\]](#) [\[PubMed\]](#)
96. Khan, M.K.A.; Abdulhameed, A.S.; Alshahrani, H.; Algburi, S. Development of chitosan biopolymer by chemically modified orange peel for Safranin O dye removal: A sustainable adsorbent and adsorption modeling using RSM-BBD. *Int. J. Biol. Macromol.* **2024**, *261*, 129964. [\[CrossRef\]](#) [\[PubMed\]](#)
97. Khoj, M.A.; Almazroai, L.S. Synthesis and characterization of treated and untreated *Dialium guineense* fruit shells as biosolid waste adsorbent: Adsorption studies of methylene blue. *Biomass Convers. Biorefin.* **2024**, *14*, 23841–23855. [\[CrossRef\]](#)
98. Inyinbor, A.A.; Bankole, D.T.; Solomon, P.; Ayeni, T.S.; Lukman, A.F. The efficiency of *Raphia hookeri* adsorbent in Indigo Carmine dye removal: Economy depth via chemometrics. *Heliyon* **2024**, *10*, e32121. [\[CrossRef\]](#)
99. Al-Hazeef, M.S.F.; Aidi, A.; Hecini, L.; Osman, A.I.; Hasan, G.G.; Althamthami, M.; Ziad, S.; Otmene, T.; Rooney, D.W. Valorizing date palm spikelets into activated carbon-derived composite for methyl orange adsorption: Advancing circular bioeconomy in wastewater treatment—A comprehensive study on its equilibrium, kinetics, thermodynamics, and mechanisms. *Environ. Sci. Pollut. Res.* **2024**, *31*, 50493–50512. [\[CrossRef\]](#)
100. Ahmed, M.; Nasar, A. Decolorization of methylene blue solution by employing magnetized *Artocarpus heterophyllus* fruit peel as a novel adsorbent. *Arab. J. Sci. Eng.* **2023**, *48*, 7647–7659. [\[CrossRef\]](#)
101. Ajab, H.; Nayab, D.; Mannan, A.; Waseem, A.; Jafry, A.T.; Yaqub, A. Comparative analysis of the equilibrium, kinetics, and characterization of the mechanism of rapid adsorption of Congo red on nano-biosorbents based on agricultural waste in industrial effluents. *J. Environ. Manag.* **2024**, *358*, 120863. [\[CrossRef\]](#) [\[PubMed\]](#)
102. Abdulhameed, A.S.; Al Omari, R.H.; Burchak, M.; Abdullah, S.; Abualhaija, M.; Algburi, S. Bio-sourced multifunctional adsorbent of chitosan and adipic acid activated-dragon fruit peels for organic dye removal from water: Eco-friendly management and valorization of biomass. *Biomass Bioenergy* **2024**, *190*, 107414. [\[CrossRef\]](#)
103. Singh, N.; Singh, R.; Shah, K.; Pramanik, B.K. Green synthesis of zinc oxide nanoparticles using lychee peel and its application in anti-bacterial properties and CR dye removal from wastewater. *Chemosphere* **2023**, *327*, 138497. [\[CrossRef\]](#)
104. Li, Z.; Zhou, M.; Liu, N.; Zhang, F.; An, K.; Xiong, X.; Fan, S.; Sun, Q.; Le, T. Engineered biochar derived from lemon peel waste for highly efficient removal of organic pollutants from water. *Arab. J. Sci. Eng.* **2023**, *16*, 105158. [\[CrossRef\]](#)
105. Sharma, M.; Sharma, K.; Kumar, D.; Gill, F.S.; Ichikawa, T.; Jain, A.; Shrivastava, K. Process analysis of aqueous ciprofloxacin adsorption by biochar–magnetite nanocomposites. *Discov. Appl. Sci.* **2025**, *7*, 1216. [\[CrossRef\]](#)
106. Ali, Z.T.A.; Abdulhusain, N.A. Containment of ciprofloxacin and copper in groundwater using nanocomposit prepared by the use of pomegranate peel extract: Characterization, kinetic, and modeling study. *Desalin. Water Treat.* **2023**, *315*, 327–341. [\[CrossRef\]](#)
107. Parlayıcı, Ş.; Baran, Y. Fruit peel incorporated alginate based magnetic hydrogel bio-composite beads for removal of hexavalent chromium. *Int. J. Biol. Macromol.* **2025**, *284*, 137946. [\[CrossRef\]](#) [\[PubMed\]](#)
108. Mohammadbagheri, Z.; Rahmati, A.; Saeedi, S.; Movahedi, B. Bio-based nanocomposite hydrogels derived from poly (glycerol tartrate) and cellulose: Thermally stable and green adsorbents for efficient adsorption of heavy metals. *Chemosphere* **2024**, *349*, 140956. [\[CrossRef\]](#)
109. Pavithra, S.; Gomathi, G.; S, S.; P.n, S.; Alkhamis, H.H.; Alrefaei, A.F.; Almutairi, M.H. Batch adsorption studies on surface tailored chitosan/orange peel hydrogel composite for the removal of Cr(VI) and Cu(II) ions from synthetic wastewater. *Chemosphere* **2021**, *271*, 129415. [\[CrossRef\]](#)
110. Foroutan, R.; Peighambaroust, S.J.; Mohammadi, R.; Peighambaroust, S.H.; Ramavandi, B. Cadmium ion removal from aqueous media using banana peel biochar/Fe₃O₄/ZIF-67. *Environ. Res.* **2022**, *211*, 113020. [\[CrossRef\]](#)
111. Chen, M.; Wang, X.; Zhang, H. Comparative research on selective adsorption of Pb(II) by biosorbents prepared by two kinds of modifying waste biomass: Highly-efficient performance, application and mechanism. *J. Environ. Manag.* **2021**, *288*, 112388. [\[CrossRef\]](#)
112. Joshi, P.; Mehta, S.; Goswami, R.N.; Srivastava, M.; Ray, A.; Khatri, O.P. Fruit waste-derived cellulose-polyaniline composite for adsorption-coupled reduction of chromium oxyanions. *Environ. Sci. Pollut. Res.* **2024**, *31*, 8719–8735. [\[CrossRef\]](#)
113. Nguyen, L.H.; Le, V.S.; Tran, L.D.; Thai, N.V.; Tram, H.T.N.; Minh, B.Q.; Nguyen, V.H. Environmental-friendly method for preparing CoFe₂O₄ coated biopolymer extracted from dragon fruit peel: Characterization and application as nanocomposite adsorbent for removal of As(III) pollutants from aqueous solution. *J. Ind. Eng. Chem.* **2023**, *118*, 432–445. [\[CrossRef\]](#)

114. Aliprandini, P.; Botelho, A.B.; Veiga, M.M.; Marshall, B.G.; Scarazzato, T.; Espinosa, D.C.R. Evaluation of biosorbents as an alternative for mercury cyanide removal from aqueous solution. *Miner. Eng.* **2023**, *204*, 108431. [\[CrossRef\]](#)
115. Ospina-Montoya, V.; Pérez, S.; Muñoz-Saldaña, J.; Forgionny, A.; Flórez, E.; Acelas, N. Performance of novel Ca-biocomposites produced from banana peel and eggshell for highly efficient removal and recovery of phosphate from domestic wastewater. *J. Environ. Manag.* **2024**, *352*, 120029. [\[CrossRef\]](#) [\[PubMed\]](#)
116. Munagapati, V.S.; Yarramuthi, V.; Kim, Y.; Lee, K.M.; Kim, D.S. Removal of anionic dyes (reactive black 5 and Congo red) from aqueous solutions using banana peel powder as an adsorbent. *Ecotoxicol. Environ. Saf.* **2018**, *148*, 601–607. [\[CrossRef\]](#) [\[PubMed\]](#)
117. Rahmat, N.A.; Ali, A.A.; Hussain, N.; Muhamad, M.S.; Kristanti, R.A.; Hadibarata, T. Removal of remazol brilliant blue R from aqueous solution by adsorption using pineapple leaf powder and lime peel powder. *Water Air Soil Pollut.* **2016**, *227*, 105. [\[CrossRef\]](#)
118. Aziri, S.; Meziane, S. Optimization of process parameters for Cr(VI) removal by seed powder of prickly pear (*Opuntia ficus-indica* L.) fruits using Taguchi method. *Desalin. Water Treat.* **2017**, *81*, 118–122. [\[CrossRef\]](#)
119. Villabona-Ortiz, Á.; Tejada-Tovar, C.; González-Delgado, Á.D.; Herrera-Barros, A.; Silvera-Charris, R. Removal of Cr(VI) ions from aqueous solution using orange peel residual biomass: Thermodynamic and sorption-desorption study. *Desalin. Water Treat.* **2020**, *203*, 309–314. [\[CrossRef\]](#)
120. Kebede, M.; Gupta Neeraj, K.; Ananda Murthy, H.C.; Bekele, W.E. Application potential of chemically modified mixed banana and orange fruit peels as adsorbents for chromium (VI) from aqueous solution. *Res. J. Chem. Environ.* **2020**, *24*, 36–49.
121. Liang, L.P.; Wang, Q.; Xi, F.F.; Tan, W.S.; Zhang, Y.T.; Cheng, L.B.; Wu, Q.; Xue, Y.Y.; Meng, X. Effective removal of Cr(VI) from aqueous solution using modified orange peel powder: Equilibrium and kinetic study. *Nat. Environ. Pollut. Technol.* **2020**, *19*, 1391–1398. [\[CrossRef\]](#)
122. Villen-Guzman, M.; Gutierrez-Pinilla, D.; Gomez-Lahoz, C.; Vereda-Alonso, C.; Rodriguez-Maroto, J.M.; Arhoun, B. Optimization of Ni (II) biosorption from aqueous solution on modified lemon peel. *Environ. Res.* **2019**, *179*, 108849. [\[CrossRef\]](#)
123. Abdić, Š.; Memić, M.; Šabanović, E.; Sulejmanović, J.; Begić, S. Adsorptive removal of eight heavy metals from aqueous solution by unmodified and modified agricultural waste: Tangerine peel. *Int. J. Environ. Sci. Technol.* **2018**, *15*, 2511–2518. [\[CrossRef\]](#)
124. Mahmood-ul-Hassan, M.; Suthor, V.; Rafique, E.; Yasin, M. Removal of Cd, Cr, and Pb from aqueous solution by unmodified and modified agricultural wastes. *Environ. Monit. Assess.* **2015**, *187*, 19. [\[CrossRef\]](#)
125. Oyewo, O.A.; Onyango, M.S.; Wolkersdorfer, C. Application of banana peels nanosorbent for the removal of radioactive minerals from real mine water. *J. Environ. Radioact.* **2016**, *164*, 369–376. [\[CrossRef\]](#)
126. Ye, L.; Gao, G.; Li, F.; Sun, Y.; Yang, S.; Qin, Q.; Wang, J.; Bai, N.; Xue, Y.; Sun, L. A comprehensive review on biochar-based materials for the safe utilization and remediation of heavy metal-contaminated agricultural soil and associated mechanisms. *J. Environ. Chem. Eng.* **2025**, *13*, 116179. [\[CrossRef\]](#)
127. Singh, R.; Goyal, A.; Sinha, S. Global insights into biochar: Production, sustainable applications, and market dynamics. *Biomass Bioenergy* **2025**, *194*, 107663. [\[CrossRef\]](#)
128. Mari Selvam, S.; Behera, B.; Chauhan, A.; Madaan, A.; Rajamanickam, R.; Akshaya, K.; Selvasembian, R. Sustainable approach of modified biochar based adsorbents towards enhanced phosphorus removal from wastewater. *J. Anal. Appl. Pyrolysis* **2025**, *188*, 107020. [\[CrossRef\]](#)
129. Hoang, L.T.T.T.; Phan, H.V.T.; Nguyen, N.N.; Dang, T.T.; Tran, T.N.; Nguyen, V.K.; Dao, M.T. Utilization of dragon fruit (*Hylocereus undatus*) peel-derived biochar for the adsorptive removal of tetracycline from aqueous solution. *Int. J. Phytoremediation* **2024**, *26*, 2313–2324. [\[CrossRef\]](#) [\[PubMed\]](#)
130. Gotore, O.; Osamu, N.; Rameshprabu, R.; Arthi, M.; Unpaprom, Y.; Itayama, T. Iodine adsorption isotherms on Matamba fruit shell stemmed biochar for wastewater re-use strategy in rural areas owing to climate change. *Chemosphere* **2022**, *303*, 135126. [\[CrossRef\]](#) [\[PubMed\]](#)
131. Cheng, D.; Ngo, H.H.; Guo, W.; Chang, S.W.; Nguyen, D.D.; Zhang, X.; Varjani, S.; Liu, Y. Feasibility study on a new pomelo peel derived biochar for tetracycline antibiotics removal in swine wastewater. *Sci. Total Environ.* **2020**, *720*, 137662. [\[CrossRef\]](#)
132. Deng, H.; Li, Q.; Huang, M.; Li, A.; Zhang, J.; Li, Y.; Li, S.; Kang, C.; Mo, W. Removal of Zn(II), Mn(II) and Cu(II) by adsorption onto banana stalk biochar: Adsorption process and mechanisms. *Water Sci. Technol.* **2020**, *82*, 2962–2974. [\[CrossRef\]](#) [\[PubMed\]](#)
133. Wu, J.; Yang, J.; Feng, P.; Huang, G.; Xu, C.; Lin, B. High-efficiency removal of dyes from wastewater by fully recycling litchi peel biochar. *Chemosphere* **2020**, *246*, 125734. [\[CrossRef\]](#)
134. Darweesh, T.M.; Ahmed, M.J. Batch and fixed bed adsorption of levofloxacin on granular activated carbon from date (*Phoenix dactylifera* L.) stones by KOH chemical activation. *Environ. Toxicol. Pharmacol.* **2017**, *50*, 159–166. [\[CrossRef\]](#)
135. de Paula Ramos, B.; Perez, I.D.; Paiano, M.S.; Vieira, M.G.A.; Boina, R.F. Activated carbons from passion fruit shells in adsorption of multimetal wastewater. *Environ. Sci. Pollut. Res.* **2022**, *29*, 1446–1457. [\[CrossRef\]](#)
136. Fernandez, M.E.; Ledesma, B.; Román, S.; Bonelli, P.R.; Cukierman, A.L. Development and characterization of activated hydrochars from orange peels as potential adsorbents for emerging organic contaminants. *Bioresour. Technol.* **2015**, *183*, 221–228. [\[CrossRef\]](#)

137. Cruz, G.J.F.; Matějová, L.; Pirilä, M.; Ainassaari, K.; Canepa, C.A.; Solis, J.; Cruz, J.F.; Šolcová, O.; Keiski, R.L. A comparative study on activated carbons derived from a broad range of agro-industrial wastes in removal of large-molecular-size organic pollutants in aqueous phase. *Water Air Soil Pollut.* **2015**, *226*, 214. [\[CrossRef\]](#)
138. Hadi, S.; Taheri, E.; Amin, M.M.; Fatehizadeh, A.; Aminabhavi, T.M. Adsorption of 4-chlorophenol by magnetized activated carbon from pomegranate husk using dual stage chemical activation. *Chemosphere* **2021**, *270*, 128623. [\[CrossRef\]](#) [\[PubMed\]](#)
139. Abdullah, M.F.; Azfaralariff, A.; Lazim, A.M. Methylene blue removal by using pectin-based hydrogels extracted from dragon fruit peel waste using gamma and microwave radiation polymerization techniques. *J. Biomater. Sci. Polym. Ed.* **2018**, *29*, 1745–1763. [\[CrossRef\]](#) [\[PubMed\]](#)
140. Ma, C.M.; Yang, B.Y.; Hong, G.B. Husk of agarwood fruit-based hydrogel beads for adsorption of cationic and anionic dyes in aqueous solutions. *Molecules* **2021**, *26*, 1437. [\[CrossRef\]](#)
141. Kaushik, J.; Kumar, V.; Garg, A.K.; Dubey, P.; Tripathi, K.M.; Sonkar, S.K. Bio-mass derived functionalized graphene aerogel: A sustainable approach for the removal of multiple organic dyes and their mixtures. *New J. Chem.* **2021**, *45*, 9073–9083. [\[CrossRef\]](#)
142. Cunha, G.D.C.; dos Santos, B.T.; Alves, J.R.; Alves Silva, I.A.; de Souza Cruz, D.R.; Romão, L.P.C. Applications of magnetic hybrid adsorbent derived from waste biomass for the removal of metal ions and reduction of 4-nitrophenol. *J. Environ. Manag.* **2018**, *213*, 236–246. [\[CrossRef\]](#)
143. Lian, J.J.; Huang, Y.G.; Chen, B.; Wang, S.S.; Wang, P.; Niu, S.P.; Liu, Z.L. Removal of molybdenum(VI) from aqueous solutions using nano zero-valent iron supported on biochar enhanced by cetyl-trimethyl ammonium bromide: Adsorption kinetic, isotherm and mechanism studies. *Water Sci. Technol.* **2018**, *2017*, 859–868. [\[CrossRef\]](#)
144. Campagnolo, L.; Morselli, D.; Magri, D.; Scarpellini, A.; Demirci, C.; Colombo, M.; Athanassiou, A.; Fragouli, D. Silk fibroin/orange peel foam: An efficient biocomposite for water remediation. *Adv. Sustain. Syst.* **2019**, *3*, 1800097. [\[CrossRef\]](#)
145. Adunphatcharaphon, S.; Petchkongkaew, A.; Greco, D.; D’Ascanio, V.; Visessanguan, W.; Avantaggiato, G. The effectiveness of durian peel as a multi-mycotoxin adsorbent. *Toxins* **2020**, *12*, 108. [\[CrossRef\]](#)
146. Malesic-Eleftheriadou, N.; Liakos, E.V.; Evgenidou, E.; Kyzas, G.Z.; Bikiaris, D.N.; Lambropoulou, D.A. Low-cost agricultural wastes (orange peels) for the synthesis and characterization of activated carbon biosorbents in the removal of pharmaceuticals in multi-component mixtures from aqueous matrices. *J. Mol. Liq.* **2022**, *368*, 120795. [\[CrossRef\]](#)
147. Sadaiyan, B.; Karunanithi, R.; Karunanithi, Y. Adsorptive removal of orange G dye from aqueous solution by ultrasonic-activated peanut shell powder: Isotherm, kinetic and thermodynamic studies. *Environ. Technol.* **2024**, *45*, 4131–4145. [\[CrossRef\]](#)
148. Li, X.; Chen, H.; Rong, K.; Gao, Q.; Jin, J.; Yi, S.; Yang, Q.; Sun, C.; Li, R.; Yin, Z.; et al. Removal of aqueous As(V) by biochar stabilized green synthesized iron nanoparticles: Optimization, mechanism and DFT insights. *J. Environ. Chem. Eng.* **2025**, *13*, 117350. [\[CrossRef\]](#)
149. Jeyaseelan, A.; Sathiyajothi, V.; Viswanathan, N.; Selvaraj, M. Regenerable green aluminium organic frameworks supported orange peel biochar/hydroxyapatite decorated chitosan/pectin hybrid composite for selective malachite green removal. *Int. J. Biol. Macromol.* **2025**, *331*, 148190. [\[CrossRef\]](#) [\[PubMed\]](#)
150. Ghedjemis, A.; Kebaili, M.; Hebbache, K.; Belebchouche, C.; Kadri, E.H. Utilizing Residual Industrial Waste as Sustainable Adsorbents for the Removal of Indigo Carmine from Contaminated Water. *Physchem.* **2025**, *5*, 21. [\[CrossRef\]](#)
151. Boyle, O.; Bo Xiao, B.; Mangwandi, C. Valorization of Banana Peel Waste into Advanced Adsorbent Beads for the Removal of Emerging Pollutants from Wastewater. *Materials* **2025**, *18*, 1084. [\[CrossRef\]](#)
152. Omanović, R.; Čopra-Janićijević, A.; Begić, S.; Đekić, M.; Sulejmanović, J. Sustainable water treatment: Fruit waste-derived ethanol extract for SiO₂ surface modification and enhanced methylene blue adsorption. *Desalin. Water Treat.* **2025**, *322*, 101146. [\[CrossRef\]](#)
153. Tolkou, A.K.; Tsoutsas, E.K.; Kyzas, G.Z.; Katsoyiannis, I.A. Sustainable use of low-cost adsorbents prepared from waste fruit peels for the removal of selected reactive and basic dyes found in wastewaters. *Environ. Sci. Pollut. Res. Int.* **2024**, *31*, 14662–14689. [\[CrossRef\]](#)
154. Şimşek, İ.; Bahadır, T.; Çelebi, H. Selective adsorption of single and binary dyestuffs by citrus peel: Characterization, and adsorption performance. *Chemosphere* **2024**, *352*, 141475. [\[CrossRef\]](#)
155. Nabizadeh Nodehi, R.; Sheikhi, R.; Gholami, M. Application of Response Surface Methodology in the photocatalytic removal of pollutants—a systematic review: Characteristics, common mistakes, and qualitative evaluation of articles. *Result. Chem.* **2024**, *8*, 101584. [\[CrossRef\]](#)
156. Karimifard, S.; Alavi Moghaddam, M.R. Application of Response Surface Methodology in physicochemical removal of dyes from wastewater: A critical review. *Sci. Total Environ.* **2018**, *640–641*, 772–797. [\[CrossRef\]](#)
157. Lingamdinne, L.P.; Vemula, K.R.; Chang, Y.Y.; Yang, J.K.; Karri, R.R.; Koduru, J.R. Process optimization and modeling of lead removal using iron oxide nanocomposites generated from bio-waste mass. *Chemosphere* **2020**, *243*, 125257. [\[CrossRef\]](#) [\[PubMed\]](#)
158. Ahmed, A.; Siyal, A.N.; Bhatia, S.; Memon, S.Q.; Mahar, A. Modified strawberry calyx as an efficient adsorbent for Ni(II) ions adsorption a central composite design approach for multivariate sorption optimization. *Desalin. Water Treat.* **2020**, *191*, 164–172. [\[CrossRef\]](#)

159. Sivarajasekar, N.; Mohanraj, N.; Balasubramani, K.; Maran, J.P.; Moorthy, I.G.; Karthik, V.; Karthikeyan, K. Optimization, equilibrium and kinetic studies on ibuprofen removal onto microwave assisted—Activated *Aegle marmelos* correa fruit shell. *Desalin. Water Treat.* **2017**, *84*, 48–58. [\[CrossRef\]](#)
160. Danish, M.; Khanday, W.A.; Hashim, R.; Sulaiman, N.S.B.; Akhtar, M.N.; Nizami, M. Application of optimized large surface area date stone (*Phoenix dactylifera*) activated carbon for rhodamin B removal from aqueous solution: Box-Behnken design approach. *Ecotoxicol. Environ. Saf.* **2017**, *139*, 280–290. [\[CrossRef\]](#)
161. Nguyen, N.T.T.; Tran, T.T.; Lam, T.V.; Phung, S.C.; Nguyen, D.T.C. Simultaneous optimization of production yield and sulfadiazine adsorption of MgFe₂O₄ loaded on prickly pear biochars using Box-Behnken design. *Environ. Sci. Pollut. Res.* **2024**, *31*, 67382–67396. [\[CrossRef\]](#)
162. Kumar, N.; Vach, M.; Saini, V.K.; Zitkova, A. Co-pyrolysis of orange peel and eggshell for oxygenated rich composite: Process optimization with response surface methodology. *J. Environ. Manag.* **2024**, *351*, 119786. [\[CrossRef\]](#)
163. Hapiz, A.; Jawad, A.H.; Alothman, Z.A.; Wilson, L.D. Mesoporous activated carbon derived from fruit by-product by pyrolysis induced chemical activation: Optimization and mechanism for fuchsin basic dye removal. *Int. J. Phytoremediation* **2024**, *26*, 1064–1075. [\[CrossRef\]](#) [\[PubMed\]](#)
164. Turk Sekulić, M.; Pap, S.; Stojanović, Z.; Bošković, N.; Radonić, J.; Šolević Knudsen, T. Efficient removal of priority, hazardous priority and emerging pollutants with *Prunus armeniaca* functionalized biochar from aqueous wastes: Experimental optimization and modeling. *Sci. Total Environ.* **2018**, *613–614*, 736–750. [\[CrossRef\]](#)
165. Ghaedi, A.M.; Vafaei, A. Applications of Artificial Neural Networks for adsorption removal of dyes from aqueous solution: A review. *Adv. Colloid Interface Sci.* **2017**, *245*, 20–39. [\[CrossRef\]](#) [\[PubMed\]](#)
166. Fiyadh, S.S.; Alardhi, S.M.; Al Omar, M.; Aljumaily, M.M.; Al Saadi, M.A.; Fayaed, S.S.; Ahmed, S.N.; Salman, A.D.; Abdalsalm, A.H.; Jabbar, N.M.; et al. A comprehensive review on modelling the adsorption process for heavy metal removal from waste water using Artificial Neural Network technique. *Heliyon* **2023**, *9*, e15455. [\[CrossRef\]](#)
167. Zhang, W.; Huang, W.; Tan, J.; Huang, D.; Ma, J.; Wu, B. Modeling, optimization and understanding of adsorption process for pollutant removal via machine learning: Recent progress and future perspectives. *Chemosphere* **2023**, *311*, 137044. [\[CrossRef\]](#)
168. Nascimento, M.X.; Santos, B.A.P.D.; Nassarden, M.M.S.; Nogueira, K.D.S.; Barros, R.G.D.S.; Golin, R.; Siqueira, A.B.D.; Vasconcelos, L.G.D.; Morais, E.B.D. Artificial neural network-based modeling of Malachite green adsorption onto baru fruit endocarp: Insights into equilibrium, kinetic, and thermodynamic behavior. *Int. J. Phytoremediation* **2024**, *26*, 1749–1763. [\[CrossRef\]](#)
169. Karaman, C.; Karaman, O.; Show, P.L.; Karimi-Maleh, H.; Zare, N. Congo red dye removal from aqueous environment by cationic surfactant modified-biomass derived carbon: Equilibrium, kinetic, and thermodynamic modeling, and forecasting via Artificial Neural Network approach. *Chemosphere* **2022**, *290*, 133346. [\[CrossRef\]](#) [\[PubMed\]](#)
170. Kooh, M.R.R.; Dahri, M.K.; Lim, L.B.L. Jackfruit seed as low-cost adsorbent for removal of malachite green: Artificial Neural Network and random forest approaches. *Environ. Earth Sci.* **2018**, *77*, 434. [\[CrossRef\]](#)
171. Vinayagam, R.; Nagendran, V.; Goveas, L.C.; Narasimhan, M.K.; Varadavenkatesan, T.; Samanth, A.; Selvaraj, R. Machine learning, conventional and statistical physics modeling of 2,4-Dichlorophenoxyacetic acid (2,4-D) herbicide removal using biochar prepared from *Vateria indica* fruit biomass. *Chemosphere* **2024**, *350*, 141130. [\[CrossRef\]](#) [\[PubMed\]](#)
172. Mendoza-Castillo, D.I.; Villalobos-Ortega, N.; Bonilla-Petriciolet, A.; Tapia-Picazo, J.C. Neural network modeling of heavy metal sorption on lignocellulosic biomasses: Effect of metallic ion properties and sorbent characteristics. *Ind. Eng. Chem. Res.* **2015**, *54*, 443–453. [\[CrossRef\]](#)
173. Saravanan, A.; Kumar, P.S.; Vo, D.V.N.; Swetha, S.; Nguenagni, P.T.; Karishma, S.; Jeevanantham, S.; Yaashikaa, P.R. Ultrasonic assisted agro waste biomass for rapid removal of Cd(II) ions from aquatic environment: Mechanism and modelling analysis. *Chemosphere* **2021**, *271*, 129484. [\[CrossRef\]](#)
174. Li, H.; Xiong, J.; Zhang, G.; Liang, A.; Long, J.; Xiao, T.; Chen, Y.; Zhang, P.; Liao, D.; Lin, L.; et al. Enhanced thallium(I) removal from wastewater using hypochlorite oxidation coupled with magnetite-based biochar adsorption. *Sci. Total Environ.* **2020**, *698*, 134166. [\[CrossRef\]](#)
175. Asbollah, M.A.; Sahid, M.S.M.; Shahrin, E.W.E.S.; Narudin, N.A.H.; Kusrini, E.; Shahri, N.N.M.; Hobley, J.; Usman, A. Dynamics and thermodynamics for competitive adsorptive removal of methylene blue and rhodamine B from binary aqueous solution onto durian rind. *Environ. Monit. Assess.* **2022**, *194*, 645. [\[CrossRef\]](#)
176. Melliti, A.; Touihri, M.; Kofroňová, J.; Hannachi, C.; Sellaoui, L.; Bonilla-Petriciolet, A.; Vurm, R. Sustainable removal of caffeine and acetaminophen from water using biomass waste-derived activated carbon: Synthesis, characterization, and modelling. *Chemosphere* **2024**, *355*, 141787. [\[CrossRef\]](#)
177. Abd El-Monaem, E.M.; Omer, A.M.; El-Subruiti, G.M.; Mohy-Eldin, M.S.; Eltaweil, A.S. Zero-valent iron supported-lemon derived biochar for ultra-fast adsorption of methylene blue. *Biomass Convers. Biorefin.* **2024**, *14*, 1697–1709. [\[CrossRef\]](#)
178. Wang, Y.; Wang, F.; Shu, L.; Wu, P.; Li, Z.; Gao, J.; Liu, H. Novel sustainable adsorbents prepared by banana/pomegranate peels via EDTA grafting for effective removal of Cd(II), Co(II), Mn(II), and Ni(II) from sewage system. *Water Air Soil Pollut.* **2023**, *234*, 131. [\[CrossRef\]](#)

179. Eissa, F.; Alsherbeny, S.; El-Sawi, S.; Slaný, M.; Lee, S.S.; Shaheen, S.M.; Jamil, T.S. Remediation of pesticides contaminated water using biowastes-derived carbon rich biochar. *Chemosphere* **2023**, *340*, 139819. [\[CrossRef\]](#)
180. Al-sareji, O.J.; Abdulzahra, M.A.; Hussein, T.S.; Shlakaa, A.S.; Karhib, M.M.; Meiczinger, M.; Grmasha, R.A.; Al-Juboori, R.A.; Somogyi, V.; Domokos, E.; et al. Removal of pharmaceuticals from water using Laccase immobilized on orange peels waste-derived activated carbon. *Water* **2023**, *15*, 3437. [\[CrossRef\]](#)
181. Wang, Q.; Wang, Y.; Yuan, L.; Zou, T.; Zhang, W.; Zhang, X.; Zhang, L.; Huang, X. Utilization of low-cost watermelon rind for efficient removal of Cd(II) from aqueous solutions: Adsorption performance and mechanism elucidation. *Chem. Eng. J. Adv.* **2022**, *12*, 100393. [\[CrossRef\]](#)
182. Nathan, R.J.; Barr, D.; Rosengren, R.J. Six fruit and vegetable peel beads for the simultaneous removal of heavy metals by biosorption. *Environ. Technol.* **2022**, *43*, 1935–1952. [\[CrossRef\]](#)
183. Guo, X.; Zhu, L.; Xu, X.; Ma, M.; Zou, G.; Wei, D. Competitive or synergetic? Adsorption mechanism of phosphate and oxytetracycline on chestnut shell-derived biochar. *J. Clean. Prod.* **2022**, *370*, 133526. [\[CrossRef\]](#)
184. Batool, S.; Shah, A.A.; Abu Bakar, A.F.; Maah, M.J.; Abu Bakar, N.K. Removal of organochlorine pesticides using zerovalent iron supported on biochar nanocomposite from *Nephelium lappaceum* (Rambutan) fruit peel waste. *Chemosphere* **2022**, *289*, 133011. [\[CrossRef\]](#) [\[PubMed\]](#)
185. Abatal, M.; Lima, E.C.; Giannakoudakis, D.A.; Vargas, J.; Anastopoulos, I.; Olguin, M.T.; Alfonso, I. Pitahaya fruit (*Hylocereus* spp.) peels evaluation for removal of Pb(II), Cd(II), Co(II), and Ni(II) from the waters. *Sustainability* **2022**, *14*, 1685. [\[CrossRef\]](#)
186. Kusri, E.; Usman, A.; Sani, F.A.; Wilson, L.D.; Abdullah, M.A.A. Simultaneous adsorption of lanthanum and yttrium from aqueous solution by durian rind biosorbent. *Environ. Monit. Assess.* **2019**, *191*, 488. [\[CrossRef\]](#)
187. Vareda, J.P. On validity, physical meaning, mechanism insights and regression of adsorption kinetic models. *J. Mol. Liq.* **2023**, *376*, 121416. [\[CrossRef\]](#)
188. Hu, Q.; Lan, R.; He, L.; Liu, H.; Pei, X. A critical review of adsorption isotherm models for aqueous contaminants: Curve characteristics, site energy distribution and common controversies. *J. Environ. Manag.* **2023**, *329*, 117104. [\[CrossRef\]](#)
189. Salvestrini, S.; Ambrosone, L.; Kopinke, F.-D. Some mistakes and misinterpretations in the analysis of thermodynamic adsorption data. *J. Mol. Liq.* **2022**, *352*, 118762. [\[CrossRef\]](#)
190. Hashem, A.; Aniagor, C.O.; Morsy, O.; Farag, S.; Aly, A.A. Adsorptive removal of acid blue 193 dye from wastewater using *Citrullus colocynthis* biomass. *Biomass Convers. Biorefin.* **2024**, *15*, 7105–7117. [\[CrossRef\]](#)
191. Azizian, S. Kinetic models of sorption: A theoretical analysis. *J. Colloid Interface Sci.* **2004**, *276*, 47–52. [\[CrossRef\]](#)
192. Plazinski, W.; Rudzinski, W.; Plazinska, A. Theoretical models of sorption kinetics including a surface reaction mechanism: A review. *Adv. Colloid Interface Sci.* **2009**, *152*, 2–13. [\[CrossRef\]](#)
193. Rudzinski, W.; Plazinski, W. On the applicability of the pseudo-second order equation to represent the kinetics of adsorption at solid/solution interfaces: A theoretical analysis based on the statistical rate theory. *Adsorption* **2009**, *15*, 181–192. [\[CrossRef\]](#)
194. Major, G.H.; Chatterjee, S.; Linford, M.R. Resolving a mathematical inconsistency in the Ho and McKay adsorption equation. *Appl. Surf. Sci.* **2020**, *504*, 144157. [\[CrossRef\]](#)
195. Ezzati, R. A new insight into the pseudo-second-order model and the physical meaning of its rate constant in adsorption. *J. Dispers. Sci. Technol.* **2025**, *46*, 222–229. [\[CrossRef\]](#)
196. Georgin, J.; Franco, D.S.P.; Netto, M.S.; Allasia, D.; Oliveira, M.L.S.; Dotto, G.L. Treatment of water containing methylene by biosorption using Brazilian berry seeds (*Eugenia uniflora*). *Environ. Sci. Pollut. Res.* **2020**, *27*, 20831–20843. [\[CrossRef\]](#) [\[PubMed\]](#)
197. Jangde, V.; Umathe, P.; Antony, P.S.; Shinde, V.; Pakade, Y. Fixed-bed column dynamics of xanthate-modified apple pomace for removal of Pb(II). *Int. J. Environ. Sci. Technol.* **2019**, *16*, 6347–6356. [\[CrossRef\]](#)
198. Khelali, A.; Benmahdi, F.; Sahnoune, D.; Sami, K.; Haciosmanoğlu, G.G.; Akram, S.; Isinkaralar, K.; Siswanta, D.; Hosseini-Bandegharai, A. Removal of AG 25 dye from aqueous solutions and treatment of real tannery wastewater by reusable magnetic iron oxide nanoparticles loaded with pomegranate pomace extract. *Environ. Res.* **2025**, *279*, 121744. [\[CrossRef\]](#)
199. Akram, M.; Bano, Z.; Bhutto, S.U.A.; Pan, J.; Majeed, M.K.; Li, L.; Xia, M.; Wang, F. Sustainable synthesis of Ce-La loaded onto Citrus limon for phosphate removal: Performance and regeneration studies. *Colloids Surf. B Biointerfaces* **2025**, *256*, 115042. [\[CrossRef\]](#) [\[PubMed\]](#)
200. Aichour, A.; Zaghouane-Boudiaf, H. Single and competitive adsorption studies of two cationic dyes from aqueous mediums onto cellulose-based modified citrus peels/calcium alginate composite. *Int. J. Biol. Macromol.* **2020**, *154*, 1227–1236. [\[CrossRef\]](#)
201. Abdelhameed, R.M.; Abdel-Gawad, H.; Hegazi, B. Effective adsorption of prothiofos (O-2,4-dichlorophenyl O-ethyl S-propyl phosphorodithioate) from water using activated agricultural waste microstructure. *J. Environ. Chem. Eng.* **2020**, *8*, 103768. [\[CrossRef\]](#)
202. Teng, B.; Zhao, Z.; Wu, J.; Xia, L.; Wang, Y.; Wang, H.; Yemele, O.M.; Adnan, M. Study on the effect of alginate coated Ca-Fe bimetallic composite biochar microspheres on the removal of short-chain PFAS. *Environ. Res.* **2025**, *285*, 122395. [\[CrossRef\]](#) [\[PubMed\]](#)

203. de Lima, H.H.C.; Llop, M.E.G.; dos Santos Maniezzo, R.; Moisés, M.P.; Janeiro, V.; Arroyo, P.A.; Guilherme, M.R.; Rinaldi, A.W. Enhanced removal of bisphenol A using pine-fruit shell-derived hydrochars: Adsorption mechanisms and reusability. *J. Hazard. Mater.* **2021**, *416*, 126167. [[CrossRef](#)] [[PubMed](#)]
204. Boudier, B.; Rida, K. Adsorption of rhodamine B, methyl orange, and phenol separately in aqueous systems by magnetic activated carbon: Optimization by central composite design. *Mater. Sci. Eng. B* **2024**, *307*, 117502. [[CrossRef](#)]

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